

ADVANCED EMU ELECTROCHEMICALLY REGENERABLE CO₂ AND MOISTURE ABSORBER MODULE BREADBOARD

FINAL REPORT

by

M.C. Lee, M. Sudar and B.J. Chang

February, 1988

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Prepared Under Contract NAS9-17307

by

Life Systems, Inc.

Cleveland, OH 44122

for

LYNDON B. JOHNSON SPACE CENTER

National Aeronautics and Space Administration

TR-769-4

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AND MOISTURE ABSORBER MODULE BREADBOARD

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. under Contract NAS9-17307 during the period of March, 1985 through January, 1988.

The Program Manager was Dr. M. C. Lee. Technical support was provided by Marty Sudar, Dr. B. J. Chang and John O. Jessup in chemical, mechanical and electrical areas, respectively.

The technical management of the program was under the directions of Messrs. Mike Lawson, Mike Rouen and Robert Cusick, Crew Systems Division, National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas.

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LIST OF ACRONYMS

EMU	Extravehicular Mobility Unit
ERCA	Electrochemically Regenerable CO ₂ and Moisture Absorption
EVA	Extravehicular Activity
HFM	Hollow Fiber Membrane
JSC	Johnson Space Center
LCG	Liquid Cooled Garment
NASA	National Aeronautics and Space Administration
PLSS	Portable Life Support System
RFP	Request for Proposal
SFE	Static Feed Electrolyzer
SMAC	Space Maximum Allowable Concentrations

ABSTRACT

The applicability of the Electrochemically Regenerable Carbon Dioxide and Moisture Absorption Technology to the advanced extravehicular mobility unit was demonstrated by designing, fabricating and testing a breadboard Absorber Module and an Electrochemical Regenerator. Test result indicated that the absorber module meets or exceeds the carbon dioxide removal requirements specified for the design and can meet the moisture removal requirement when proper cooling is provided. Carbon dioxide concentration in the vent gas stream was reduced from 0.52 kPa (3.9 mm Hg) to 0.027 kPa (0.20 mm Hg) for the full five-hour test period. Vent gas dew point was reduced from inlet values of 294 K (69 F) to 278 K (41 F) at the outlet. The regeneration of expended absorbent was achieved by the electrochemical method employed in the testing.

An absorbent bed using microporous hydrophobic membrane sheets with circulating absorbent is shown to be the best approach to the design of an Absorber Module based on sizing and performance. Absorber Module safety design, comparison of various absorbents and their characteristics, moisture absorption and cooling study and subsystem design and operation time-lining study were also performed.

SUMMARY

In current and past space missions, metabolic carbon dioxide removal during extravehicular activity has been accomplished by reacting the carbon dioxide with lithium hydroxide. This reaction is irreversible. For future Space Station extravehicular activity, which is estimated at 2,000 hr/yr, using the current method of carbon dioxide removal will require large amounts of expendables. To minimize the amount of expendables, a regenerative extravehicular activity carbon dioxide removal technique is required.

This report documents breadboard hardware development work of an electrochemically regenerable carbon dioxide and moisture removal technology for the Space Station extravehicular activity missions. This technology is based on carbon dioxide and moisture absorbing into aqueous alkaline absorbent and electrochemical regeneration of the expended absorbent. The hardware includes a breadboard Absorber Module which will replace the existing lithium hydroxide cartridge on the Portable Life Support System and an Electrochemical Regenerator which will be located aboard the Space Station to be used for the regeneration of the expended absorbent from the Absorber Module.

The Electrochemically Regenerable Carbon Dioxide and Moisture Absorption concept is designed to eliminate the shortcomings of other potential regenerative carbon dioxide and moisture removal techniques, such as metal oxides or metal hydroxides. The concept for carbon dioxide removal is based on the same absorption and reaction chemistry as lithium hydroxide, providing similar high carbon dioxide capacity and low absorbent volume requirements for efficient storage of the metabolic carbon dioxide generated during extravehicular activity. Moisture is also absorbed into the liquid absorbent due to the difference in water vapor pressures of the vent gas and the absorbent. Structural integrity and proper containment of the absorbent is maintained because the absorbent is an aqueous solution retained in microporous hydrophobic membrane compartments. The aqueous solution provides for the exchange of expended and fresh absorbent by diffusion at a gas/absorbent interface. This mechanism decreases the gas void volume and total gas/absorbent surface area requirements compared to solid absorbents such as lithium hydroxide and metal oxides. At the completion of the extravehicular activity, the aqueous absorbent becomes the electrolyte for the electrochemical regeneration process on-board the primary space vehicle.

Past carbon dioxide absorber developments, utilizing a hollow fiber membrane absorber showed no performance degradation during 60 cycles of testing. A maximum absorption utilization of 75% and a regeneration efficiency of 63% were observed with the test hardware. The present program is an extension of this development and investigates the ways to improve the designs of the Absorber Module and Electrochemical Regenerator through breadboard hardware development and testing. The main objectives of the program were to demonstrate the applicability of the electrochemically regenerable carbon dioxide and moisture removal techniques to the advanced extravehicular mobility unit and to design, fabricate and test breadboard hardware consisting of an Absorber Module, an Electrochemical Regenerator Module and test stands and other accessories for the above.

The Absorber Module is designed to remove all metabolic carbon dioxide produced at 0.091 kg/hr (0.20 lb/hr) at an average metabolic rate of 293 W (1,000 BTU/hr) during a five-hour extravehicular activity. The optimized Absorber Module was one which utilized thin microporous membrane sheets to provide absorbent space with high gas-liquid interface area. The membranes are stacked together with supporting spacer screens in between and sealed to provide separate vent gas and liquid absorbent flow paths. The liquid absorbent is contained in alternate membrane compartments. Vent gas flows through the adjacent compartments with carbon dioxide diffusing through the hydrophobic membranes to the gas-liquid interface where the carbon dioxide and hydroxide combine to form a carbonate. The liquid absorbent is circulated through the membrane compartments. This reduces the overall module volume since much of the absorbent can be efficiently contained in the absorbent headers. Absorber module cooling is required to remove the exothermic heat of the carbon dioxide absorption reaction. A cooling coil in the absorbent header provides the cooling function. Particulate/trace contaminant filters are provided in both the vent gas inlet and outlet headers.

The Electrochemical Regenerator is designed to provide regeneration of all of the expended absorbent from the Absorber Module within a ten-hour period. Expended absorbent enters the feed compartment of the Electrochemical Regenerator and a portion of the absorbent feed flows across the electrode assembly, where the absorbent solution is regenerated (carbonate is converted back to hydroxide). Gaseous oxygen and carbon dioxide are produced at the anode and hydrogen is produced at the cathode.

The Absorber Module Test Stand provides the process fluid requirements for characterizing the performance of the Absorber Module. Four Absorber Module tests were performed. In the first run, the vent gas flow and pressure were 2.8 dm³/sec (6 acfm) and 55 kPa (8 psia), respectively. The inlet partial pressure of carbon dioxide was maintained at 0.28 kPa (2.1 mm Hg) for a five-hour period, during which time the outlet partial pressure of carbon dioxide was steady at 0.020 kPa (0.15 mm Hg). The inlet partial pressure of carbon dioxide was then increased to 0.52 kPa (3.9 mm Hg) for an additional 1.5 hour. The outlet partial pressure of carbon dioxide during this period was 0.047 kPa (0.35 mm Hg). The carbon dioxide absorption efficiency remained above 92% throughout the run. A second Absorber Module run, at vent gas conditions of 2.8 dm³/sec (6 acfm), 55 kPa (8 psia) and 0.52 kPa (3.9 mm Hg) partial pressure of carbon dioxide, was continued for 8.5 hours. The carbon dioxide removal efficiency remained above 93% through the first 6.0 hours of testing and was still above 84% at the end of the run. The third run was performed at atmospheric pressure. The inlet partial pressure of carbon dioxide was maintained at 0.52 kPa (3.9 mm Hg) for 5.5 hours. With the outlet partial pressure of carbon dioxide remaining below (0.75 mm Hg) for a removal efficiency of 81%. During the run the inlet partial pressure of carbon dioxide was increased to 1.33 kPa (10 mm Hg) for approximately 20 minutes. Even at this high inlet partial pressure of carbon dioxide, the outlet partial pressure of carbon dioxide was below 0.23 kPa (1.75 mm Hg) for 82.5% removal efficiency.

Although the Absorber Module was not designed for the absorption of metabolic moisture from the vent gas, it was believed that the module had the capability of doing so. Run No. 4 verified this, with the vent gas dew point being reduced from 294 K (69 F) to 278 K (41 F) in passing through the Absorber Module.

The Electrochemical Regenerator Test Stand was used to provide the desired test conditions for characterization of the Electrochemical Regenerator. The testing indicated that at 25 A and 326 K (128 F) that the expended absorbent at 32% carbonate and 1.3% hydroxide could be regenerated at a rate of 0.19 cm³/sec (0.70 in³/min) to an absorbent composition of 26.0% hydroxide and 10.3% carbonate.

An absorbent study was performed to investigate the properties of several candidate absorbents. These properties included carbon dioxide absorption capacity per unit volume, hydroxide, carbonate and bicarbonate solubilities, moisture absorption capability, heat of reaction, pH and conductivity. As a result of this study, cesium hydroxide was chosen as the best absorbent.

An absorbent safety design effort resulted in the development of an improved Absorber Module concept with back-up levels of protection in the unlikely event of an absorbent leak. The protective features include highly microporous hydrophobic membranes, stringent quality control during membrane bed fabrication, an accumulator to accommodate any volume expansion due to carbon dioxide and moisture absorption, back-up hydrophobic membranes at the membrane bed outlet and in the outlet gas filter, a liquid sensor in the outlet vent gas header, and an acid-impregnated carbon in the outlet gas filter to neutralize any potential absorbent leakage.

Additional work was performed in the areas of humidity control, accumulator design and prototype subsystem operating procedures and time-lining.

KEY ACCOMPLISHMENTS

- Designed, fabricated and tested a breadboard Absorber Module and Electrochemical Regenerator.
- Demonstrated the applicability of the electrochemically regenerable carbon dioxide (CO₂) removal technique to the advanced extravehicular mobility unit (EMU).
- Showed that an absorbent bed using microporous hydrophobic membrane sheets with circulating absorbent is the best approach to the design of an Absorber Module based on sizing and performance.
- Demonstrated that the Absorber Module meets or exceeds the CO₂ removal requirements specified for the design, and that it can meet the moisture removal requirement when proper cooling is provided.
- Demonstrated that the regeneration of expended absorbent can be achieved by the electrochemical method employed in the testing.
- Determined that the flight Absorber Module weighs 24 kg (52 lb), occupies 17 dm³ (0.60 ft³) and requires 1.2 W (4.1 Btu/hr) of electrical power. The Electrochemical Regenerator Subsystem weighs 42 kg (93 lb), occupies 68 dm³ (2.4 ft³) and requires 450 W (1,540 Btu/hr) of electrical power.
- Optimized the absorbent selection, the Absorber Module safety design and the humidity control capability of the Absorber Module.

INTRODUCTION

In current and past space missions, metabolic CO_2 removal during Extravehicular Activity (EVA) has been accomplished by reacting the CO_2 with lithium hydroxide (LiOH). This reaction is irreversible. For future Space Station EVA which is estimated at 2,000 hr/yr (per Request for Proposal (RFP) No. 9-BC73-2-4-51P), using the current method of CO_2 removal will require large amounts of expendables. To minimize the amount of expendables, a regenerative EMU CO_2 removal technique is required.

This report documents breadboard hardware development work of an electro-chemically regenerable CO_2 and moisture removal technology for the Space Station EVA missions. The technology is based on CO_2 and moisture absorbing into aqueous alkaline absorbent and electrochemical regeneration of expended absorbent. The hardware, resulting from the effort described herein, will include a breadboard Absorber Module which will replace the existing LiOH cartridge on the Portable Life Support System (PLSS) backpack and an Electrochemical Regenerator which will be located aboard the Space Station to be used for the regeneration of the expended absorbent from the Absorber Module.

Background

A typical block diagram of the PLSS application depicting the atmospheric revitalization loop, the liquid coolant loop and controller connections for the various PLSS components is presented in Figure 1. The concepts of CO_2 and moisture absorption by liquid absorbent and electrochemical absorbent regeneration have demonstrated great promise for regenerative CO_2 and moisture removal for the PLSS. The CO_2 /water absorber is shown as a component in the atmospheric revitalization loop where the vent gas coming directly from the breathing mask enters the loop. The debris trap and trace contaminant control functions can be combined with the absorber component. The inlet process air to the absorber is warm, moist and debris-free containing metabolic CO_2 .

Prior Concepts

In the past, several concepts were investigated for the development of a regenerable CO_2 removal system for PLSS application. Initially, direct replacement⁽¹⁾ of the LiOH by metallic oxide or metallic hydroxide pellets was attempted. Compounds of zinc, silver and magnesium were investigated for their CO_2 absorption and regeneration characteristics. These concepts were eliminated due to the loss of pellet structural integrity and fragmentation with repeated regeneration.

Other concepts based on the reaction chemistry of alkaline carbonate materials reacting with CO_2 to form bicarbonate materials were investigated.⁽²⁾ The regeneration method of these concepts is based on the thermal and/or vacuum decomposition of bicarbonate species to its original carbonate form. Similar to the metallic oxide or hydroxide concepts, the structural integrity of the

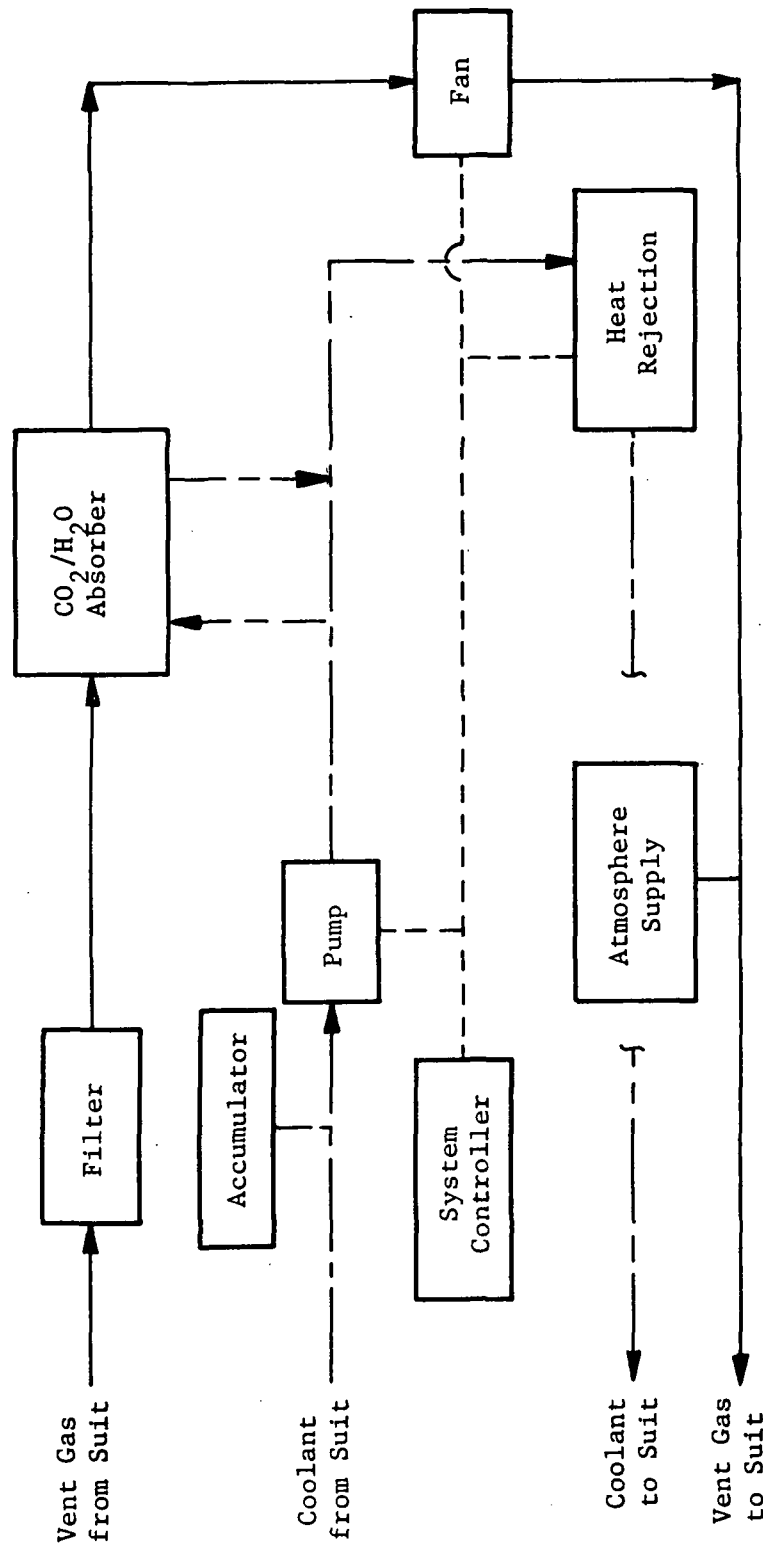


FIGURE 1 PLSS BLOCK DIAGRAM

solid form is lost upon repeated regeneration. One method which overcomes the loss of absorbent integrity upon regeneration suspends the carbonate absorbent in a porous polymer sheet.⁽³⁻⁵⁾ Testing of this concept has demonstrated a reduction in CO_2 absorption capacity of about 25% after 60 regeneration cycles. Also, high gas void volumes are required resulting in excessive EVA volumes for the backpack application.

Another proposed concept utilizes vacuum to strip the CO_2 from an aqueous carbonate absorbent solution.⁽⁶⁾ The shortcoming of this concept is that CO_2 and water are continuously lost overboard to the vacuum vent and moisture balance in the absorbent solution is continually altered.

Electrochemically Regenerable CO_2 and Moisture Absorption Concept

The Electrochemically Regenerable CO_2 and Moisture Absorption (ERCA) concept, which is shown in Figure 2, has been designed to eliminate the shortcomings of other potential regenerative CO_2 and moisture removal techniques. The ERCA concept for CO_2 removal is based on the same absorption and reaction chemistry as LiOH . This provides the similar high CO_2 absorption rate capacities and low absorbent volume requirements for efficient storage of metabolic CO_2 generated during EVA. Moisture is also absorbed into the liquid absorbent due to the difference in water vapor pressures of the vent gas and the absorbent. Structural integrity and proper containment of the absorbent is maintained because the absorbent is an aqueous solution retained in microporous hydrophobic membrane compartments. The aqueous solution provides for the exchange of expended and fresh absorbent by diffusion at a gas/absorbent interface. This mechanism decreases the gas void volume and total gas absorbent surface area requirements for the ERCA concept compared to the solid absorbents such as LiOH , metal oxides or alkaline carbonates. At the completion of the EVA the aqueous absorbent becomes the electrolyte for the electrochemical regeneration process on-board the primary space vehicle.

Past ERCA Developments

An initial ERCA conceptual study was conducted by Life Systems, Inc. (Life Systems) under company sponsorship. Subsequent development and test programs were funded by National Aeronautics and Space Administration (NASA) under Contracts NAS2-8666^(7,8) and NAS9-15218.⁽⁹⁾ The former program evaluated an ERCA CO_2 absorber where the electrochemical regeneration hardware was contained within the absorber. Multiple cycles of absorption and regeneration were performed. The cyclic testing demonstrated no performance degradation during the initial 60 cycles of testing. A maximum absorption utilization of 75% and a regeneration efficiency of 63% were observed with the test hardware. These performance levels validated the ERCA concept but left some question as to whether final flight weight and volume objectives could be met. The latter program was to perform a conceptual design of a CO_2 absorber that uses an aqueous absorbent and can be regenerated aboard a space vehicle. It demonstrated, through bench-top testings at a fractional capacity, the feasibility of a selected hollow fiber membrane absorber and electrochemical regeneration concept.

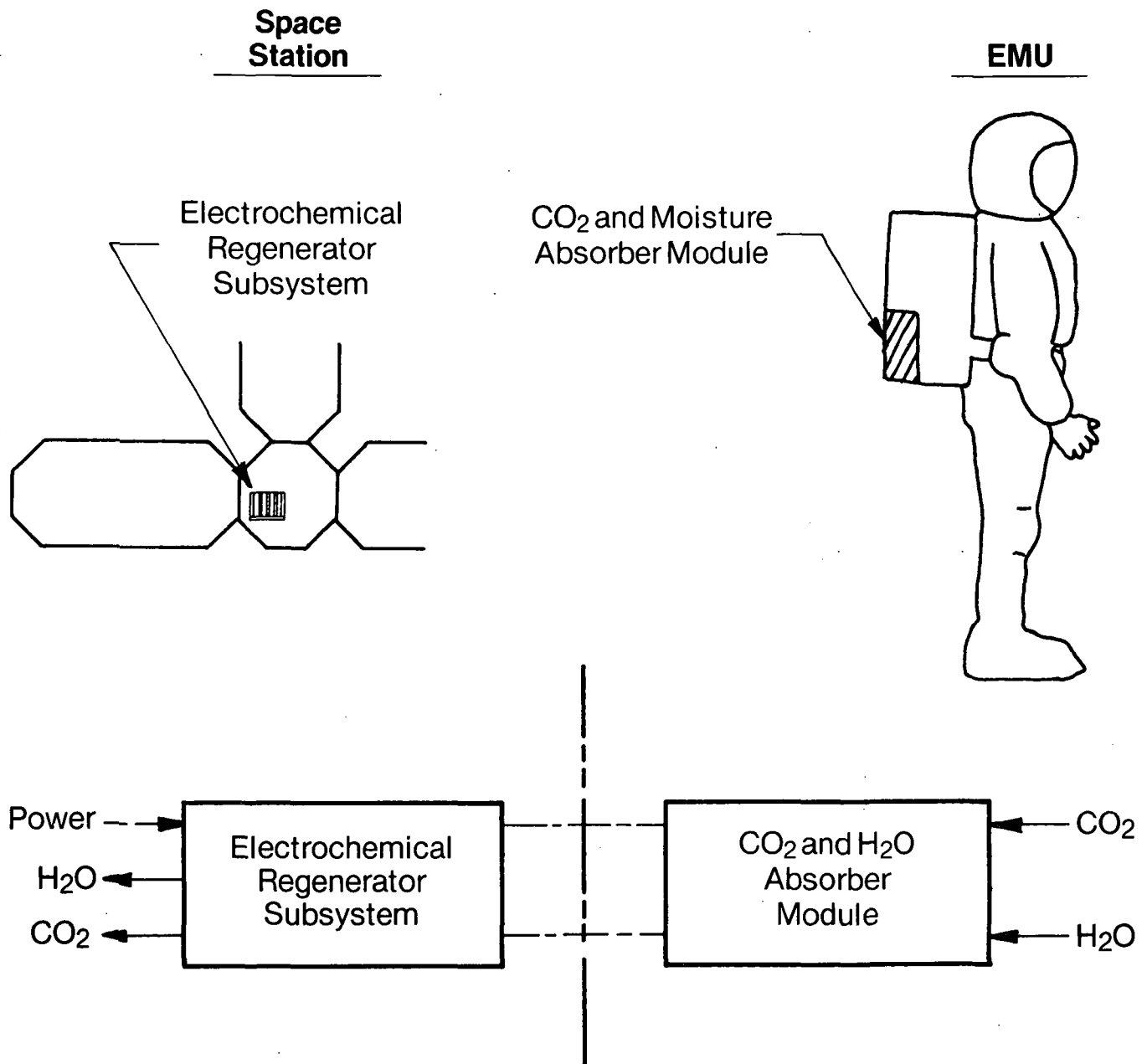


FIGURE 2 ERCA SYSTEM CONCEPT

The present program is an extension of that activity and investigates the ways to improve the designs of the Absorber Module and the Electrochemical Regenerator through breadboard hardware development and testing. The volume of the resulting Absorber Module is competitive with the existing nonregenerable technique and, for multi-missions, clearly has a launch weight performance improvement. Breadboard and flight hardware weight, power and volume information is provided in the conclusion section.

Program Objectives

The objectives of the program were to:

1. Demonstrate applicability of electrochemically regenerable CO₂ removal techniques to the advanced EMU.
2. Design, fabricate and test breadboard hardware consisting of:
 - Absorber Module
 - Electrochemical Regenerator Module
 - Test Stands and other accessories for the above
3. Demonstrate through testing that electrochemically regenerable CO₂ removal concept offers a distinct equivalent weight and volume savings for multi-EVA Space Station missions.
4. Perform absorbent characterization and safety studies.
5. Perform humidity control study and design.
6. Perform time-lining study of the operation, service and maintenance of the ERCA system.

Program Organization

To meet the above objectives, the program was divided into four tasks plus the data and program management functions. The four tasks were:

- 1.0 Design and fabricate an Absorber Module and an Electrochemical Regenerator.
- 2.0 Design and fabricate test stands for the above consisting of Absorber Module Test Stand, Electrochemical Regenerator Test Stand and CO₂ Analysis equipment.
- 3.0 Perform development testing of the Absorber Module and the Electrochemical Regenerator.
- 4.0 Deliver the Absorber Module and Electrochemical Regenerator and associated test equipment to Johnson Space Center (JSC) and provide on-site support (installation and demonstration tests.)

End Products

The end products of this contractual effort are:

1. Absorber Module
2. Electrochemical Regenerator Module
3. Absorber Module Test Stand
4. Electrochemical Regenerator Test Stand
5. CO₂ Analysis Equipment
6. Installation at JSC and Test Support
7. A Final Report summarizing the development effort, data generated, conclusions reached and recommendations for future activities

Report Organization

The following sections include separate discussions on the Absorber Module design and fabrication, and the Electrochemical Regenerator design and fabrication. The test equipment for the above are described, and the results of the Absorber Module and Electrochemical Regenerator performance testing are discussed in subsequent sections. A discussion of the product assurance aspects, conclusions concerning the development, recommendations for future studies and references cited in the report comprise the final sections.

ABSORBER MODULE

The requirements for the Absorber Module and the design concepts and preliminary designs of the module, its components and module cooling are discussed in this section.

Design Requirements

An astronaut's metabolic CO₂ production rate during EVA depends on his metabolic rate, which can range from 88 to 586 W (300 to 2,000 Btu/hr). The corresponding CO₂ production rate ranges from 0.03 to 0.18 kg/hr (0.06 to 0.40 lb/hr). At an average metabolic rate of 293 W (1,000 Btu/hr) the CO₂ production rate is 0.093 kg/hr (0.20 lb/hr). The Absorber Module shall be able to remove all metabolic CO₂ produced during a five-hour EVA. There are other requirements for the design of the module which include the flow rate, operation temperature and pressure, relative humidity, dew point temperatures, suit-in and suit-out CO₂ partial pressures of vent gas, vent gas flow pressure drop and the overall module volume. These are listed in Table 1.

Absorber Module Design

This section discusses the design of an Absorber Module that can satisfy the performance and mechanical requirements specified in Table 1. This section is divided into five subsections: (1) Design Approach, (2) Absorbent Bed Assembly, (3) Absorbent Circulation, (4) Absorber Module Cooling and (5) Absorber Module Assembly.

TABLE 1 ABSORBER MODULE DESIGN SPECIFICATIONS

Crew Size	1
EVA Time, hr	5
Metabolic Rate, W (BTU/hr)	
Nominal	293 (1,000)
Range	88-586 (300-2,000)
CO ₂ Absorption Requirement, kg (lb)	
Average	0.46 (1.00)
CO ₂ Absorption Rate, kg/hr (lb/hr)	
Nominal	0.093 (0.20)
Range	0.03-0.18 (0.06-0.40)
Module Inlet CO ₂ Partial Pressure, Pa (mm Hg)	
Nominal	507 (3.8)
Range	227-1,332 (1.7-10.0)
Module Outlet CO ₂ Partial Pressure, Pa (mm Hg)	
Nominal	0.0 (0.0)
Range	0-666 (0.0-5.0)
System Pressure, kPa (psia)	
Nominal	55.2 (8.0)
Range	41-101 (6.0-14.7)
Vent Gas Composition	N ₂ /O ₂ /CO ₂ /H ₂ O Vapor
Vent Gas Flow Rate, acdm (acfm)	
Nominal	170 (6.0)
Range	99-269 (3.5-9.5)
Vent Gas Temperature, K (F)	
Nominal	297 (75)
Range	289-305 (60-89)
Vent Gas Relative Humidity, %	
Nominal	90
Range	60-100
Vent Gas Dew Point Temperature, K (F)	
Nominal	295.6 (72)
Range	281-301 (45-82)
Allowable Vent Gas Pressure Drop, Pa (in H ₂ O)	112 (0.45)
Coolant Type	Water
Coolant Flow Rate, Maximum, kg/hr (lb/hr)	9.1 (20) (a)
Coolant Temperature, K (F)	
Nominal	294.4 (70) (a)
Range	289-301 (60-82) (a)
Allowable Coolant ₃ Pressure Drop, kPa (psid)	20.7 (3.0) (a)
Module Volume, dm ³ (ft ³)	13.2 (0.45)
Module Thickness, Maximum, dm (ft)	1.78 (0.58)
Radiative Heat Sink Temperature Range, K (F)	
Module-Provided Heat Sink	294-300 (70-80)
Deep Space Heat Sink	156-256 (-180-0)

(a) Assumed value.

Design Approach

The design of the Life Systems' Absorber Module employs a concept known to be most effective in removing acidic gases from gas streams. It uses an aqueous alkaline absorbent containing chemicals which react with absorbed CO_2 . Gas absorption processes that involve chemical reactions in the liquid phase have higher rate of absorption and greater capacity of the liquid solution to absorb the solute gas than physical absorption systems.

The chemical reaction mechanisms involved in the absorption of CO_2 into the absorbent are shown in Figure 3. The extent of the second reaction, the conversion of CO_3 to HCO_3 , depends on the level of CO_2 concentration and the operating conditions of the system. A previous study⁽¹⁰⁾ on the $\text{K}_2\text{CO}_3\text{-KHCO}_3\text{-CO}_2\text{-H}_2\text{O}$ system indicates that at partial pressure of carbon dioxide ($p\text{CO}_2$) of 507 Pa (3.8 mm Hg) the equilibrium conversion of K_2CO_3 to KHCO_3 can be as high as 20% at the operating conditions of the Absorber Module. In addition to these chemical reactions, there are many other processes involved which include:

- Transport of CO_2 to the gas-liquid interface.
- Absorption of CO_2 into the absorbent at the interface.
- Transport of reaction products to bulk absorbent.
- Transport of fresh absorbent to the interface.

As can be seen in the figure, moisture can also be absorbed in the absorbent if the water vapor pressure of the absorbent is maintained at a lower level than that of the incoming vent gas. This is due to the phenomenon called "vapor pressure depression," which occurs when an involatile solute is added to a volatile solvent. This creates the driving force for moisture to diffuse from the bulk vent gas to the absorbent interface where it is absorbed.

Providing sufficient amount of absorbent, gas-liquid interface area and maintaining as large an absorption mass transfer driving force as possible are key conditions for designing an effective Absorber Module. The designs of the Absorber Module presented in this report are the result of maximizing the aforementioned key factors within allowed design constraints.

Absorbent Bed Assembly

Requirements for a most efficient absorbent bed are:

- Provide space for required amount of absorbent
- Provide large, well-defined gas-liquid interface area between absorbent and vent gas
- Provide sufficient space for vent gas flow

Two concepts can be considered for meeting the above requirements. These are hollow fiber membrane tubes and microporous membrane sheets.

Hollow fiber membrane (HFM) tubes provide space for containing aqueous absorbent, as well as gas-liquid interface between the absorbent and

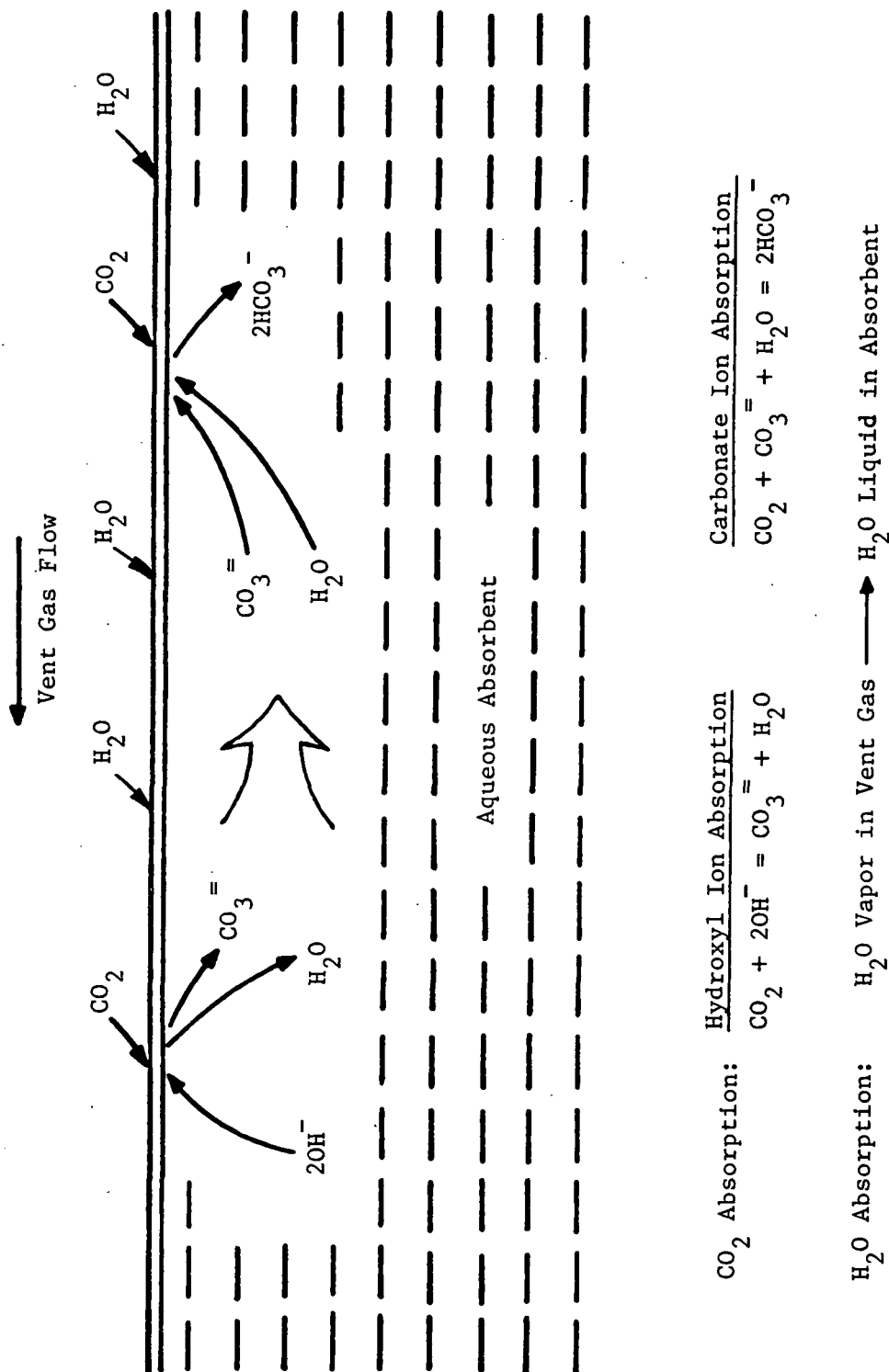


FIGURE 3 CO₂ AND MOISTURE ABSORPTION MECHANISMS

vent gas. The preliminary sketch of the tube bed assembly is shown in Figure 4 together with that of the membrane sheet bed. With the HFM tube absorbent bed, the liquid absorbent is contained inside the tubes. Vent gas flows across the outside of the tubes with CO_2 and moisture diffusing through the porous tube wall to the gas-liquid interface.

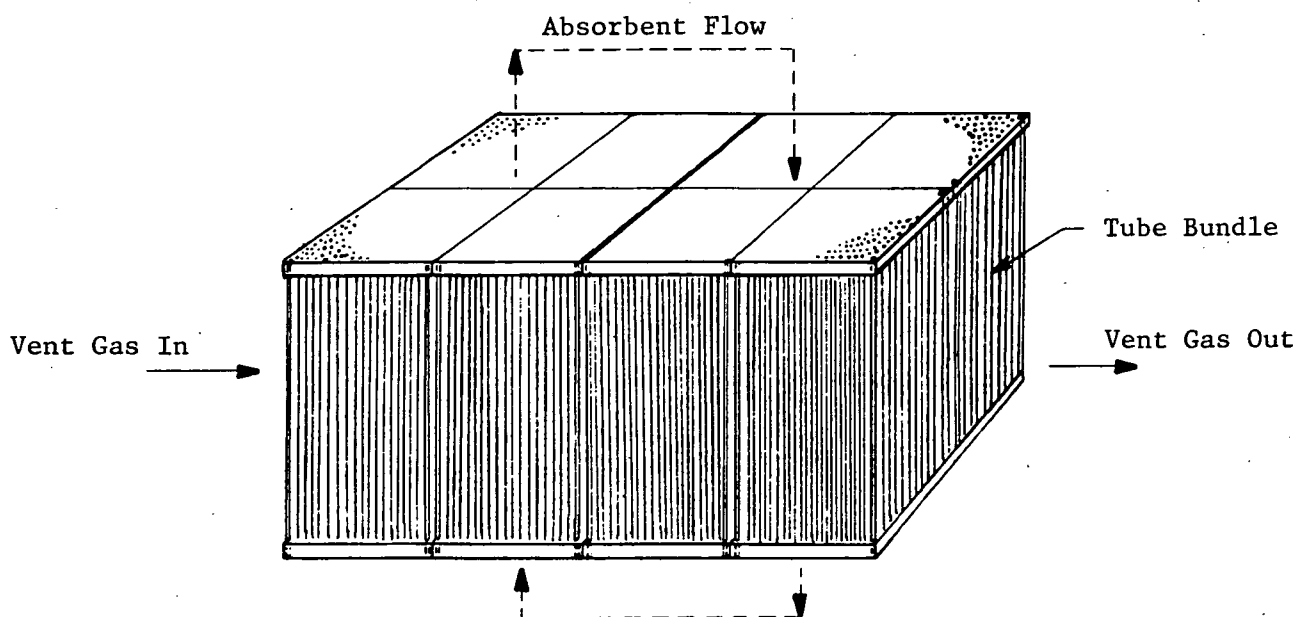
Thin microporous membrane sheets can be used for providing absorbent space and also high gas-liquid interface area. The membranes stacked together with supporting spacer screens in between and sealed as shown in Figure 4 can provide separate paths for both vent gas and liquid absorbent and also provide gas/absorbent interface. The liquid absorbent is contained in alternate membrane compartments. Vent gas flows through the adjacent compartments with CO_2 diffusing through the hydrophobic microporous membrane to the gas-liquid interface. The screens provide proper membrane spacing and provide mixing (turbulence) in the flow paths.

It is most advantageous to contain the entire amount of absorbent in the absorbent bed. In this design, which may be called "stationary absorbent" design, all the absorbent to participate in the absorption is in the absorbent bed. However, due to the membrane wall volumes and external open space required for the flow of vent gas, the overall absorbent bed volume requirement is several times as large as the absorbent volume. This is shown in Figure 5 for the HFM tube and the membrane sheet absorbent bed arrangements.

For example, the volume of the absorbent bed for retaining 6.1 dm^3 (0.215 ft^3) of absorbent, which is the projected absorbent requirement for removing 0.45 kg (1.0 lb) of metabolic CO_2 during a 5-hour EVA, exceeds 27 dm^3 (0.95 ft^3), which is too large.

An alternative to this "stationary absorbent" concept is the "circulating absorbent" concept. The functional schematics of these two concepts are shown in Figure 6. In the circulating absorbent design, the absorbent in the headers also participates in the absorption by circulating through the bed, thus replacing the expended absorbent. This is accomplished by means of an absorbent circulation pump. This makes it possible for the absorbent bed volume to be much smaller than in the stationary absorbent design. In this design the increased concentration driving force makes up for the reduced gas-liquid interface area of the smaller absorbent bed compared to the stationary absorbent design. Comparison of the two design concepts are given in Table 2. Comparison of the HFM tube absorbent bed and the membrane sheet absorbent bed was performed to determine the optimum arrangement. It was discovered that the commercially available HFM tubes have a relatively thick wall (tube outside diameter = 1.9 mm (0.075 in), tube wall thickness = 0.41 mm (0.016 in)). Additionally, HFM tube manufacturers indicated that maximum practical tube packing density was 50% (50% open area). Higher packing densities lead to tube potting problems. Since the absorbent solution is contained within the inner tube wall, the above factors (low packing density and thick tube wall) lead to inefficient storage of absorbent in the absorbent bed, and resultant large absorbent bed and module volume. Table 3 provides information comparing the HFM tube absorbent bed and membrane sheet absorbent bed arrangements. One of the major problems associated with the HFM tubes is their hydrophilicity.

Membrane Tube Absorbent Bed



Membrane Sheet Absorbent Bed

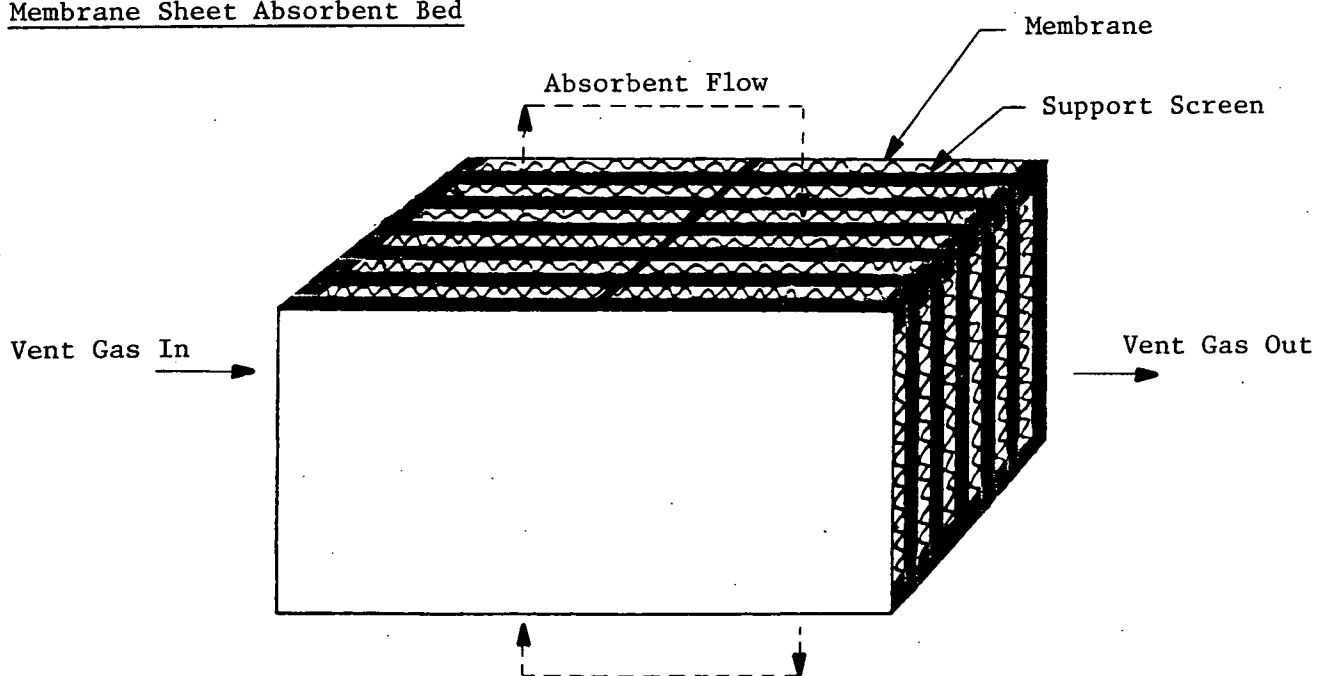
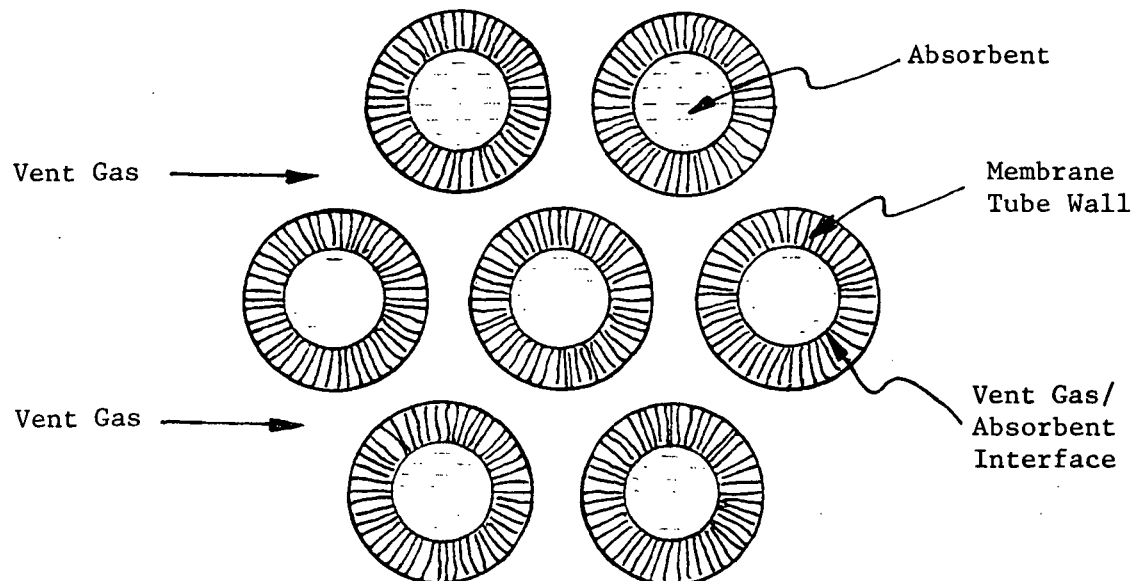


FIGURE 4 MEMBRANE MATERIAL TYPES

Membrane Tube Absorbent Bed



Membrane Sheet Absorbent Bed

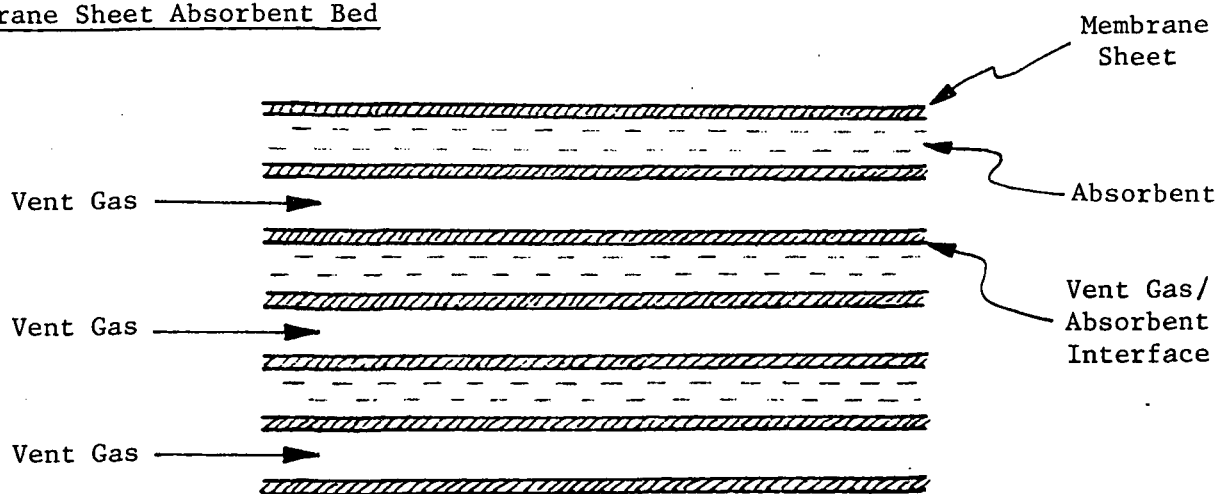
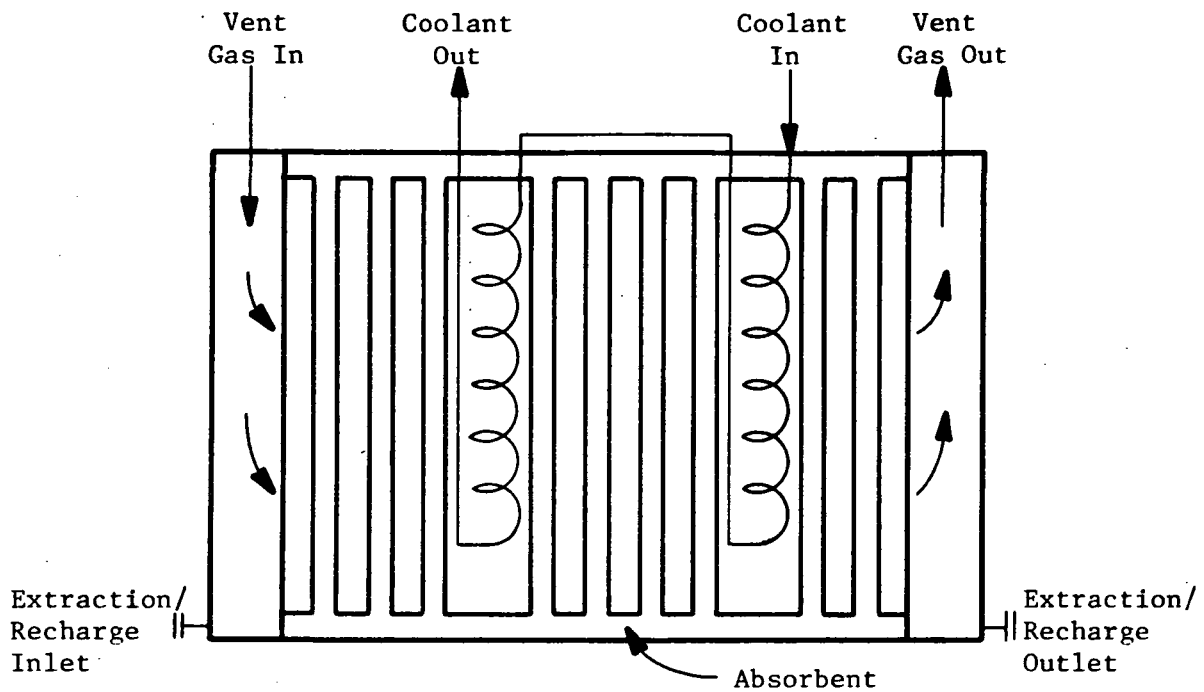


FIGURE 5 CROSS SECTION OF MEMBRANE SHEET AND TUBE ABSORBENT BEDS

Stationary Absorbent



Circulating Absorbent

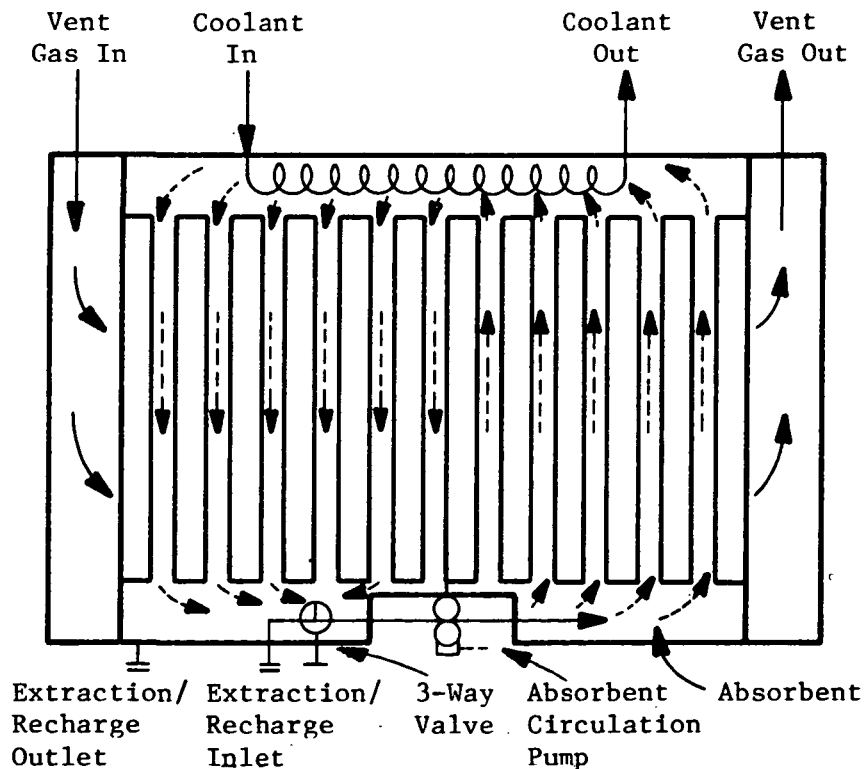


FIGURE 6 ABSORBER MODULE CONCEPTUAL DESIGNS

TABLE 2 STATIONARY VERSUS CIRCULATING ABSORBENT
DESIGN COMPARISON

	<u>Stationary</u>	<u>Circulating</u>
Advantages	<ul style="list-style-type: none">• Simpler operation	<ul style="list-style-type: none">• Smaller module volume• Effective cooling• Higher absorbent utilization efficiency• More uniform absorption rate• Simpler absorbent bed fabrication• Passive cooling feasible
Disadvantages	<ul style="list-style-type: none">• Larger module volume• Less effective cooling• Lower absorbent utilization efficiency	<ul style="list-style-type: none">• Power required for pump

TABLE 3 COMPARISON OF ABSORBER MODULES MADE BY MEMBRANE SHEET AND HFM TUBE

	Membrane Sheet ^(a)	HFM Tube ^(b)
Surface Property	Hydrophobic	Hydrophilic
Dimension, cm (in)		
Length	27.9 (11.0)	64.8 (25.5)
Height	35.3 (13.9)	17.3 (6.8)
Width	17.8 (7.0)	17.8 (7.0)
Overall Volume, dm ³ (ft ³)	17.6 (0.62)	20.4 (0.72)
Vent Gas Flow Delta P, cm Water (in Water)	1.5 (0.60)	1.5 (0.60)
Interface Area, m ² (ft ²)	6.2 (67)	4.2 (45)
Absorbent in Bed, %	37	21
Number Required, ea	180	18,000

(a) Based on using 4-mil thick membranes and 20-mil thick support screens.

(b) Based on using polysulfone HFM tubes of 43-mil ID and 75-mil OD and 50% packing density.

As such, the slightest positive pressure differential between the tube inside (absorbent) and tube outside (vent gas) will result in absorbent being pushed through the tube wall into the vent gas space. The membrane sheets, due to their hydrophobic nature, provide absorbent retention even under fairly high differential pressures (140 kPa (20 psi)). It is also seen that the membrane sheet arrangement provides more liquid-gas interface area, more absorbent solution in the bed (as opposed to in the headers), fewer component pieces and a more compact size, all with a significantly lower overall module volume.

Absorbent Bed Fabrication

The ERCA absorbent bed fabrication consists of stacking up and bonding the membranes and screens within an assembly fixture. This fixture permits proper alignment of the membranes during bonding and curing but does not become a permanent part of the bed section. The membranes and screens are bonded along two sides and in the corners to prevent cross leakage of the liquid and gas streams. The bonding is accomplished by applying an epoxy adhesive directly to the two appropriate membrane edges. Alternate flow compartments are bonded on opposite sides to obtain a "cross-flow" arrangement. The overall membrane bed is composed of several smaller bed subsections. This method permits pressure testing of the individual bed subsections prior to their assembly into the absorbent bed frame. The pressure testing procedure consists of filling the liquid compartments with water and applying pressure. If no water leaks are detected at the liquid compartment bonds or in the gas compartments, the individual bed subsection is considered to be acceptable for use in the complete absorbent bed.

The individual absorbent bed subsections are installed into the absorbent bed frame and are bonded in the corners of the frame and to the adjacent individual absorbent beds. When the frame is filled with the proper number of individual absorbent beds, a solid top plate is bonded in place to insure that the membrane/screen stack is tightly packed. This will prevent movement of the stack during pressure cycling, thus minimizing the chance of membrane damage due to stretching/rubbing.

Upon completion of the assembly, the absorbent bed is once again pressure tested. During the actual bed fabrication, two leaks were observed. Both leaks were at the bond between two individual bed subsections (this made sense since all of the individual bed subsections had previously passed the pressure check). These two leaks were repaired by closing off the compartments with additional epoxy. The pressure check was repeated and the absorbent bed was acceptable.

After several days of absorption testing, however, the membrane bed began to show signs of leakage. It is believed that this leakage was due to absorbent volume expansion (caused by CO₂ and moisture absorption) within the absorbent bed, causing increased absorbent pressure (relative to vent gas) which stretched and damaged the membranes. The absorbent bed was not believed to be faulty, but rather was unable to tolerate the high pressure encountered during operation. The current absorber module design uses an accumulator to accommodate the absorbent volume expansion which occurs during operation, thus, minimizing pressure build-up within the absorbent bed.

A second absorbent bed was fabricated. Some changes were made in the assembly procedure to improve quality control and reliability, as well as absorption performance.

The new absorbent bed fabrication involves additional steps which provide improved quality control and reliability. The microporous hydrophobic membrane is sealed around its outer edge and each membrane core is pressure tested to check for membrane or edge-seal leaks. The success rate of the membrane core testing was approximately 95%. Following the pressure test the membrane cores are assembled into an absorbent bed subsection using an absorbent bed assembly fixture. As in the previous case, this process consists of bonding in one membrane core at a time and alternating between liquid and gas compartments as determined by location of the bonded edges. A total of six absorbent bed subsections were manufactured, each consisting of approximately 30 membrane cores. The absorbent bed is assembled as six subsections for two reasons. Fabrication time is reduced since more than one subsection can be assembled at a time. The second benefit is that the subsection can be pressure checked prior to going into the full-size absorbent bed. This provides a second check on membrane/edge-bond integrity. If leaks are found they can be repaired more easily at the subsection level, and if leaks cannot be repaired only that subsection is lost. All six of the subsections were successfully pressure tested.

The six absorbent bed subsections are then bonded into a polysulfone frame which becomes the finished absorbent bed. The subsections are bonded in one at a time. When assembly is complete, the whole absorbent bed is pressure tested. This test was also successful.

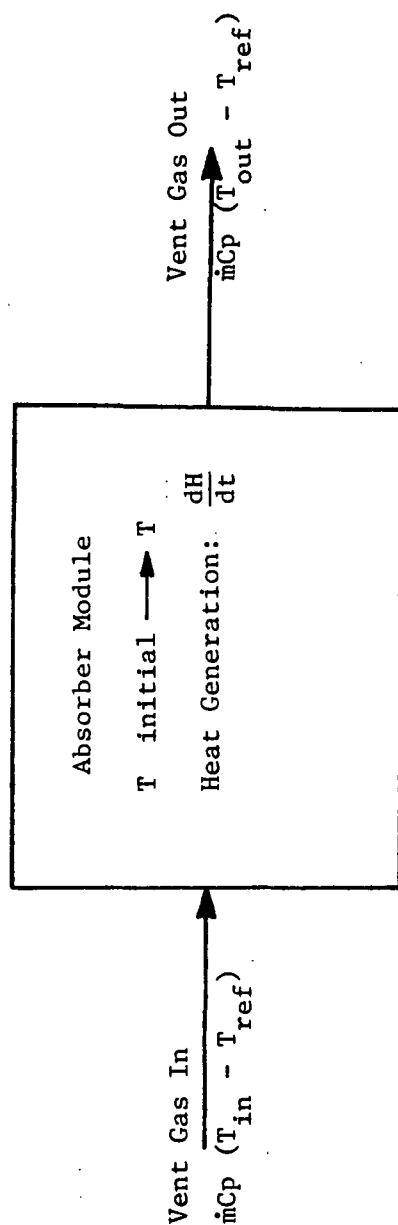
Absorbent Circulation

The circulation of absorbent in the Absorber Module will be done by a miniature positive displacement pump which has a maximum flow rate of $300 \text{ cm}^3/\text{min}$ (0.0106 cfm). By running this pump at a flow rate of $87 \text{ cm}^3/\text{min}$ (0.0030 cfm), the entire volume of absorbent, 6.1 dm^3 (0.215 ft^3) can be circulated four times through the tubes during the five hour EVA time. Total power consumption for this pump is estimated to be about 6.6 Whr (23 Btu). This power can be supplied by a rechargeable battery of approximately 34 to 54 cm^3 (2.0 to 3.2 in^3).

Absorber Module Cooling

Due to the exothermic nature of the absorption reaction into alkaline absorbent, the temperature of the module rises as the reaction progresses. The rate of heat generated during the CO_2 absorption reaction is estimated to be 61 W (207 Btu/hr). Unless adequate cooling is provided, the module temperature will gradually rise, resulting in rising temperature of outgoing vent gas. The temperature rise of the module with EVA duration without cooling is modelled in Figure 7 and shown in Figure 8.

Passive cooling, i.e., cooling of the module by radiative heat transfer, was first investigated. When EMU-provided heat sink temperatures of 294-300 K (70-80 F) were used, the module radiation surface area requirements were too



Heat Generation = Enthalpy Change in Vent Gas and Module

$$\frac{dH}{dt} = (\dot{m}Cp)_{Vent\ Gas} \cdot (T_{out} - T_{in}) + (MCp)_{Module} \cdot \frac{dT}{dt}$$

FIGURE 7 ABSORBER MODULE ENERGY BALANCE

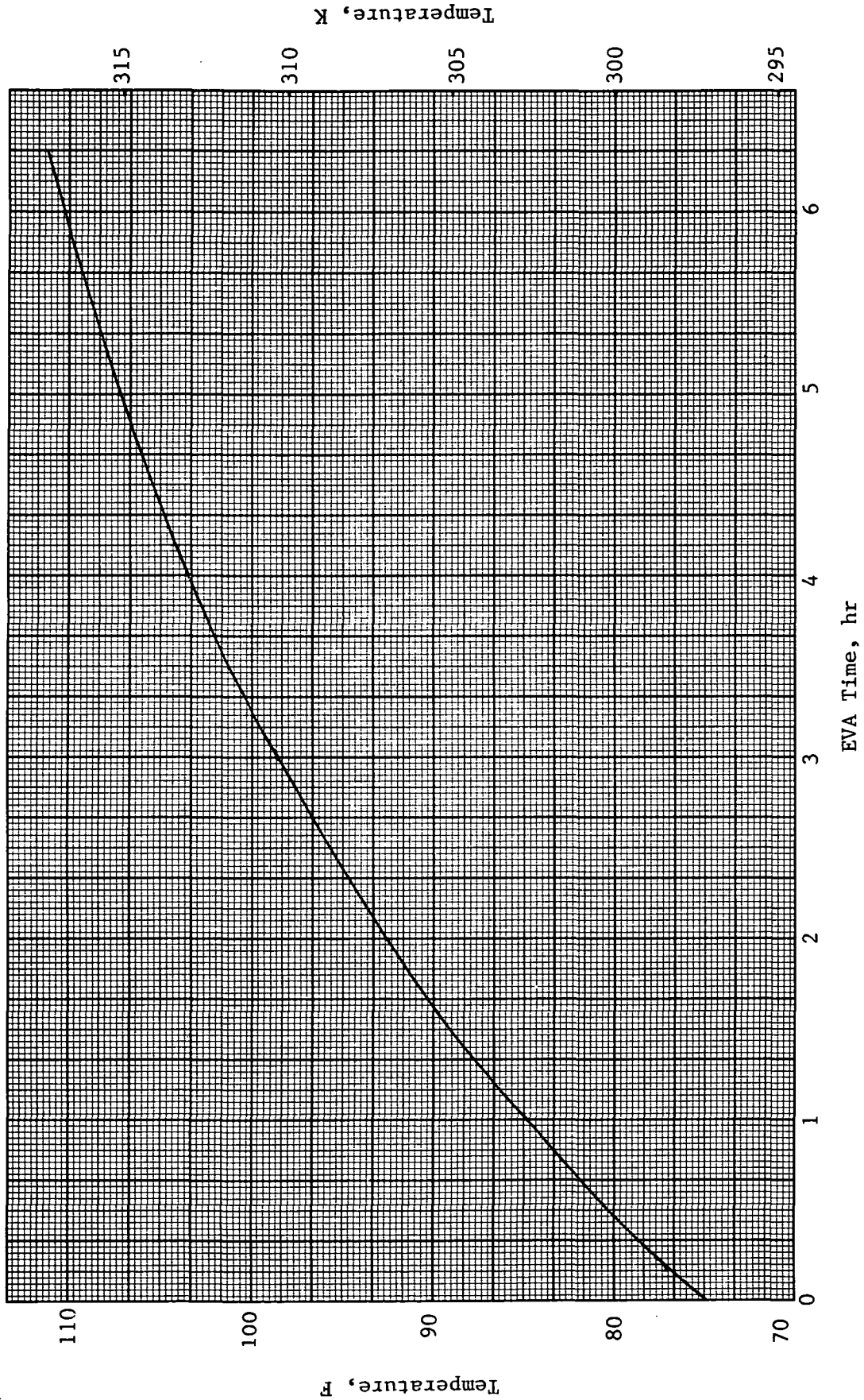


FIGURE 8 ABSORBER MODULE TEMPERATURE CHANGE WITHOUT COOLING DUE TO CO₂ ABSORPTION

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high ($>0.93 \text{ m}^2$ (10 ft^2)) (see Figure 9). The use of deep space heat sink at an average temperature of 217 K (-70 F) gave reasonable surface area requirements (0.093 m^2 ($\sim 1.0 \text{ ft}^2$)). The mathematical modelling and its results are given in Figures 10 and 11.

For this program, however, active cooling using cooling water within the specified temperature range given in Table 1 was used for the module cooling. A W-shaped stainless steel cooling coil of 6.4 mm (0.25 in) OD, 58 cm (23 in) long and 116 cm^2 (18 in^2) surface area was located in the top header near the discharge of the absorbent circulation pump with cooling water flow to be countercurrent with the absorbent flow. Energy and mass balances of the Absorber Module based on active cooling are shown in Figure 12.

Moisture absorption, although not a requirement for the breadboard hardware, can be accomplished by the absorber module. This process, however, also results in heat generation. At the nominal moisture absorption rate of 0.11 kg/hr (0.25 lb/hr), the heat generation is estimated to be 77 W (263 Btu/hr). Absorber module cooling requirements must be increased accordingly if both CO_2 and moisture absorption are to be done.

Absorber Module Assembly

The Absorber Module consists of an absorbent bed assembly, an absorbent circulation/extraction/recharge assembly, vent gas purifying components, a module cooling assembly and an accumulator. Its functional block diagram is shown in Figure 13.

As described earlier, the absorbent bed assembly contains absorbent solution and provides gas-liquid interface area for the absorption of CO_2 in the vent gas stream. The vent gas is filtered by a filter/active carbon bed assembly to remove any particulate material and trace contaminant gas. The filter/active carbon bed will be a replaceable item, and will be accessible via a removable vent gas header cover plate.

The absorbent headers provide space for absorbent storage and circulation and cooling coil installation. The absorbent circulation pump provides continuous absorbent flow through the absorbent headers, past the cooling assembly and through the bed. The accumulator provides space for the absorbent volume increase which occurs due to CO_2 and/or moisture absorption. (The accumulator was not part of the original Absorber Module design, but was added after problems were experienced with absorbent expansion and membrane damage with the original absorbent bed.)

With the membrane sheet arrangement, the membranes and spacers will be stacked up and assembled inside of a supporting frame. The membrane sheet assembly will then become part of the absorbent headers, with the frame being sealed to the module housing using O-ring seals. The membrane sheet assembly and frame will be removable from one side of the module for maintenance or replacement.

ELECTROCHEMICAL REGENERATOR

The requirements for the Electrochemical Regenerator and the design concepts and preliminary design of the module and its components are discussed in this section. The original Electrochemical Regenerator design concept utilized a

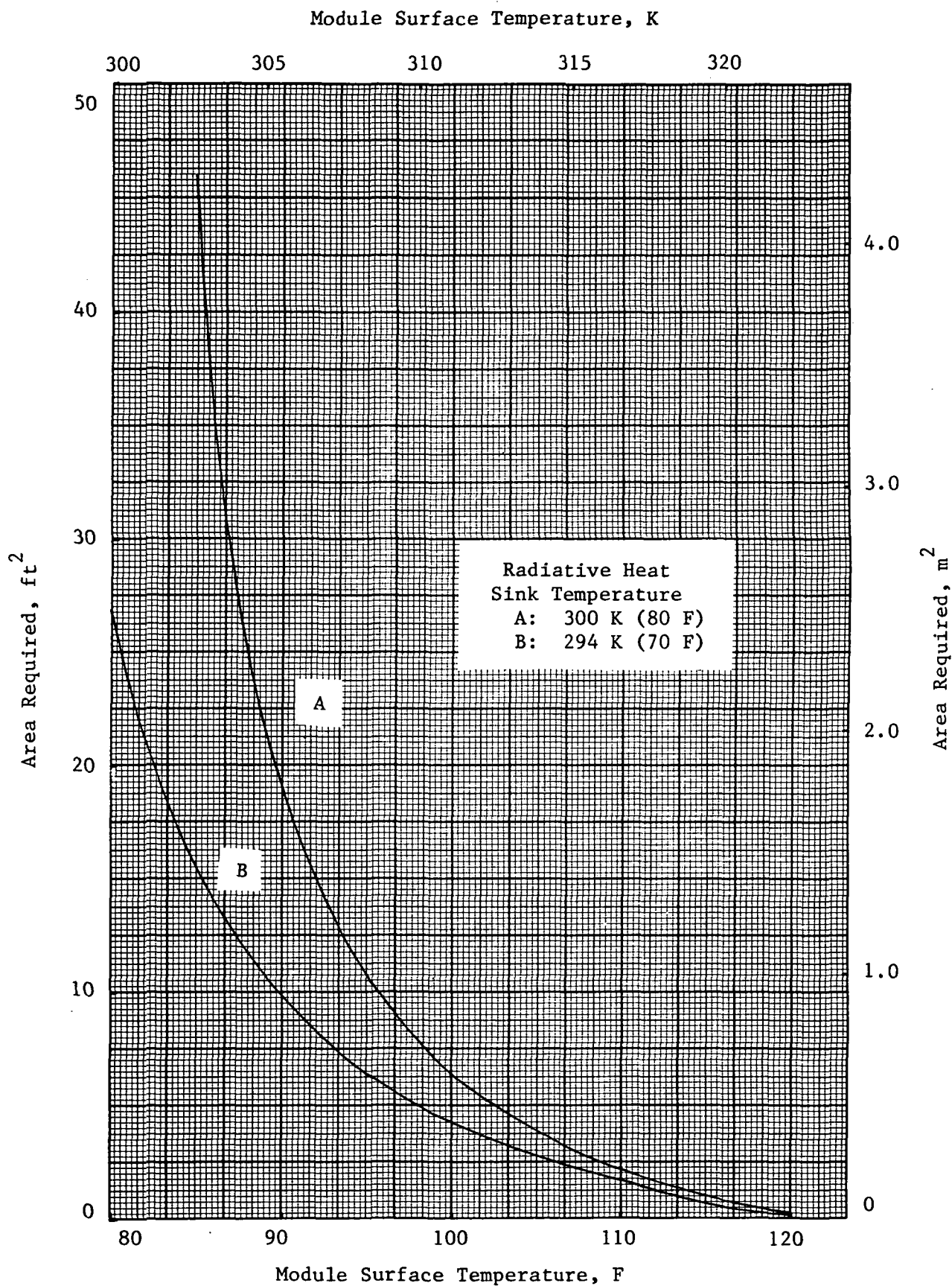
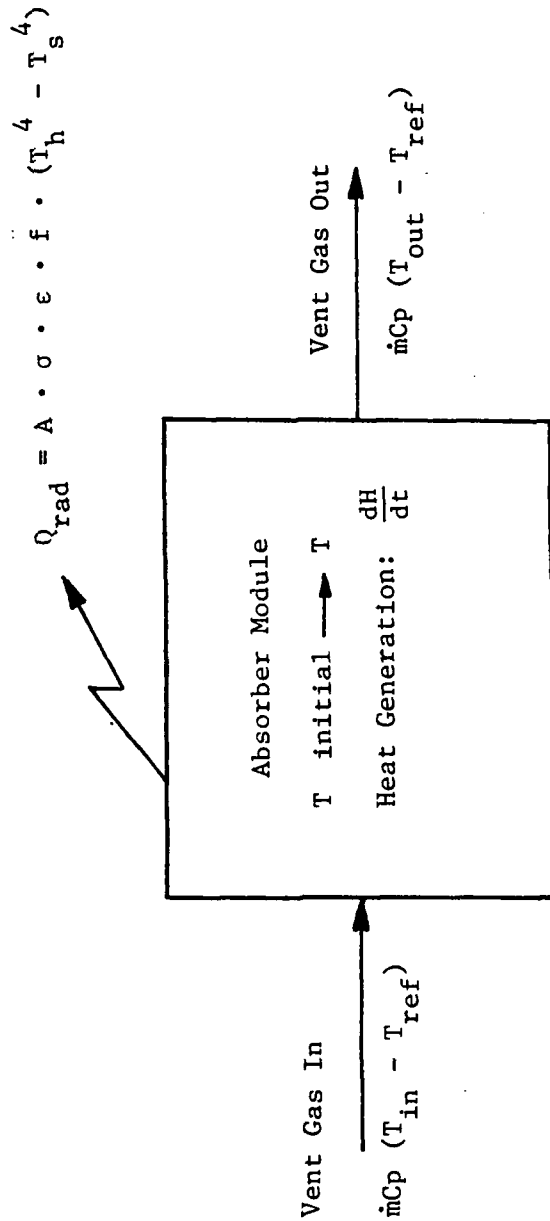


FIGURE 9 RADIATION SURFACE AREA REQUIREMENT VERSUS MODULE SURFACE TEMPERATURE



Heat Generation = Enthalpy Change in Vent Gas and Module + Radiation

$$\frac{dH}{dt} = (\dot{m}Cp)_{Vent\ Gas} \cdot (T_{out} - T_{in}) + (MCp)_{Module} \cdot \frac{dT}{dt} + Q_{rad}$$

FIGURE 10 ABSORBER MODULE ENERGY BALANCE WITH PASSIVE COOLING

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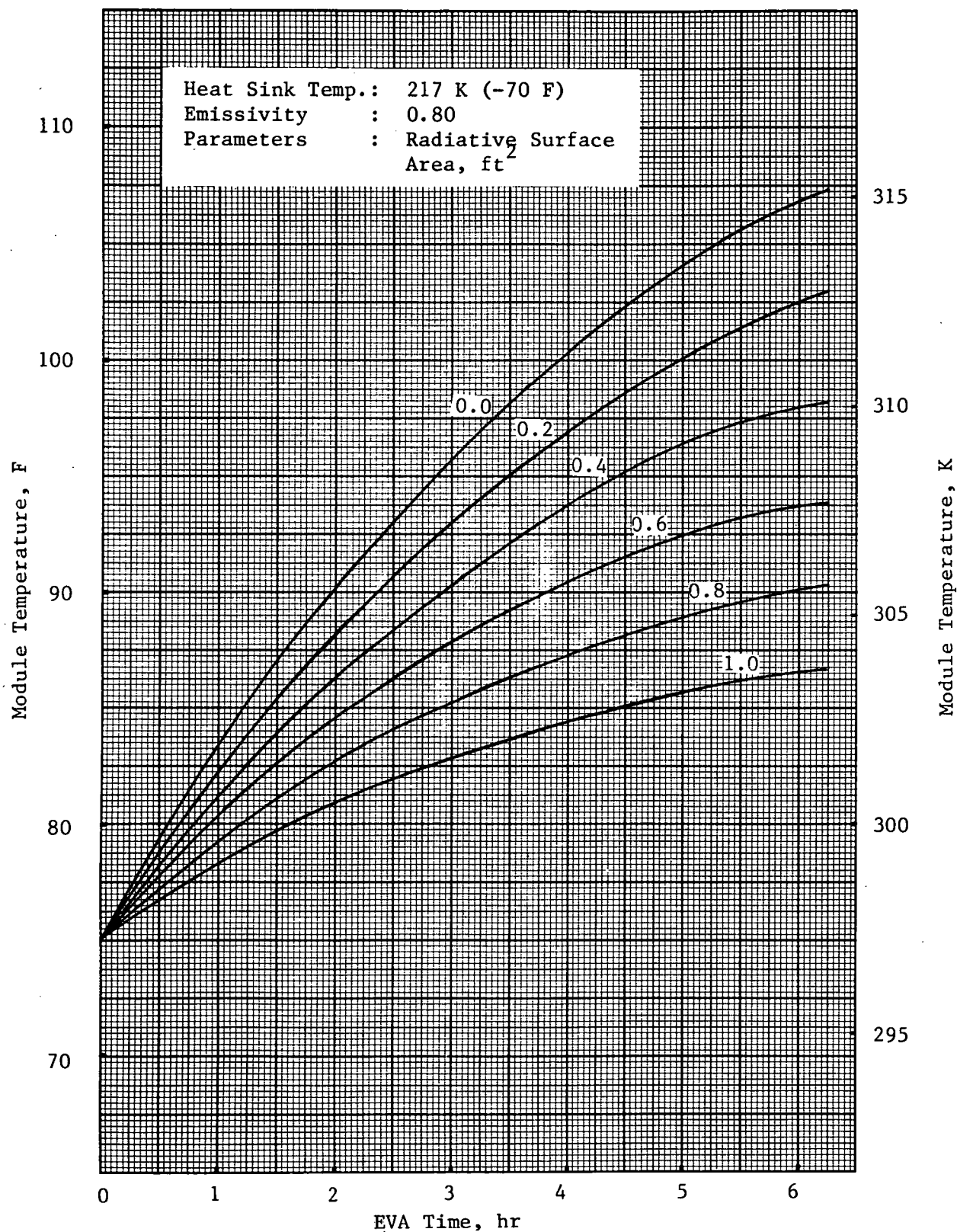
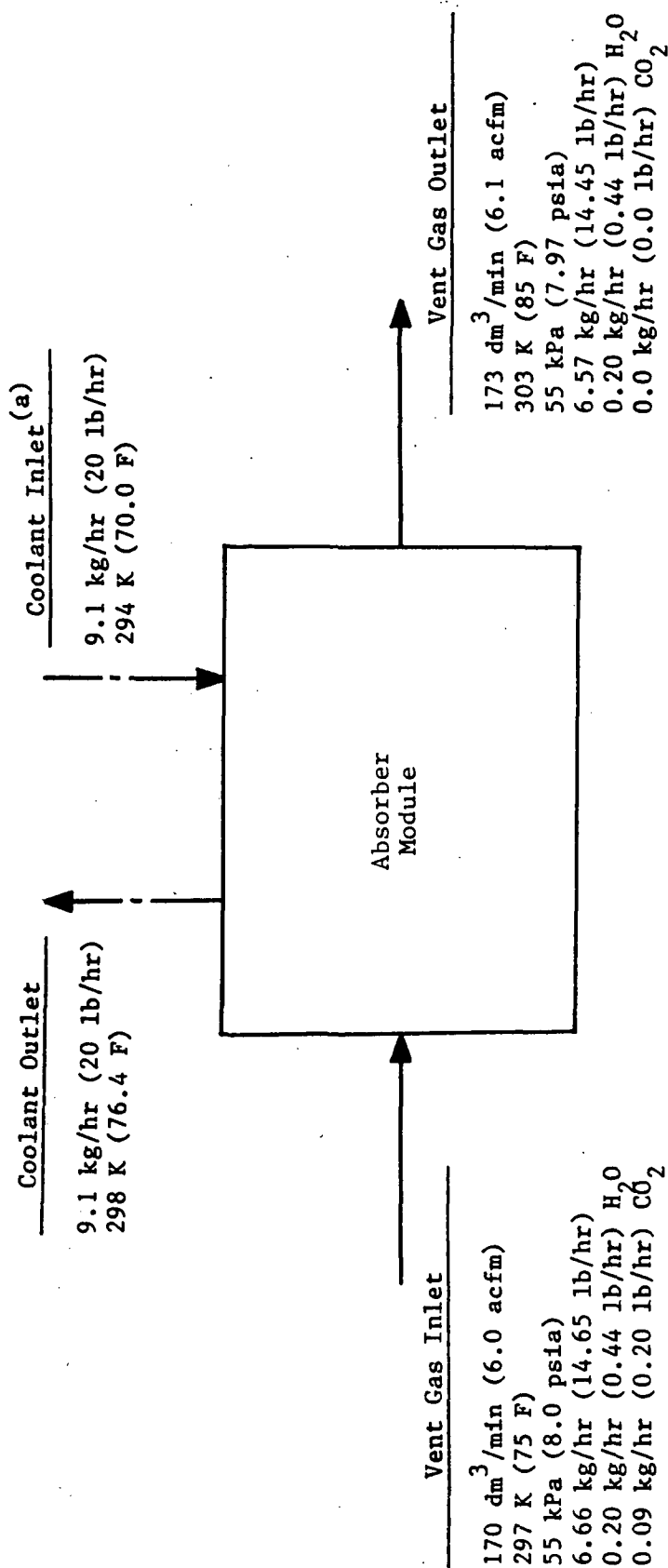
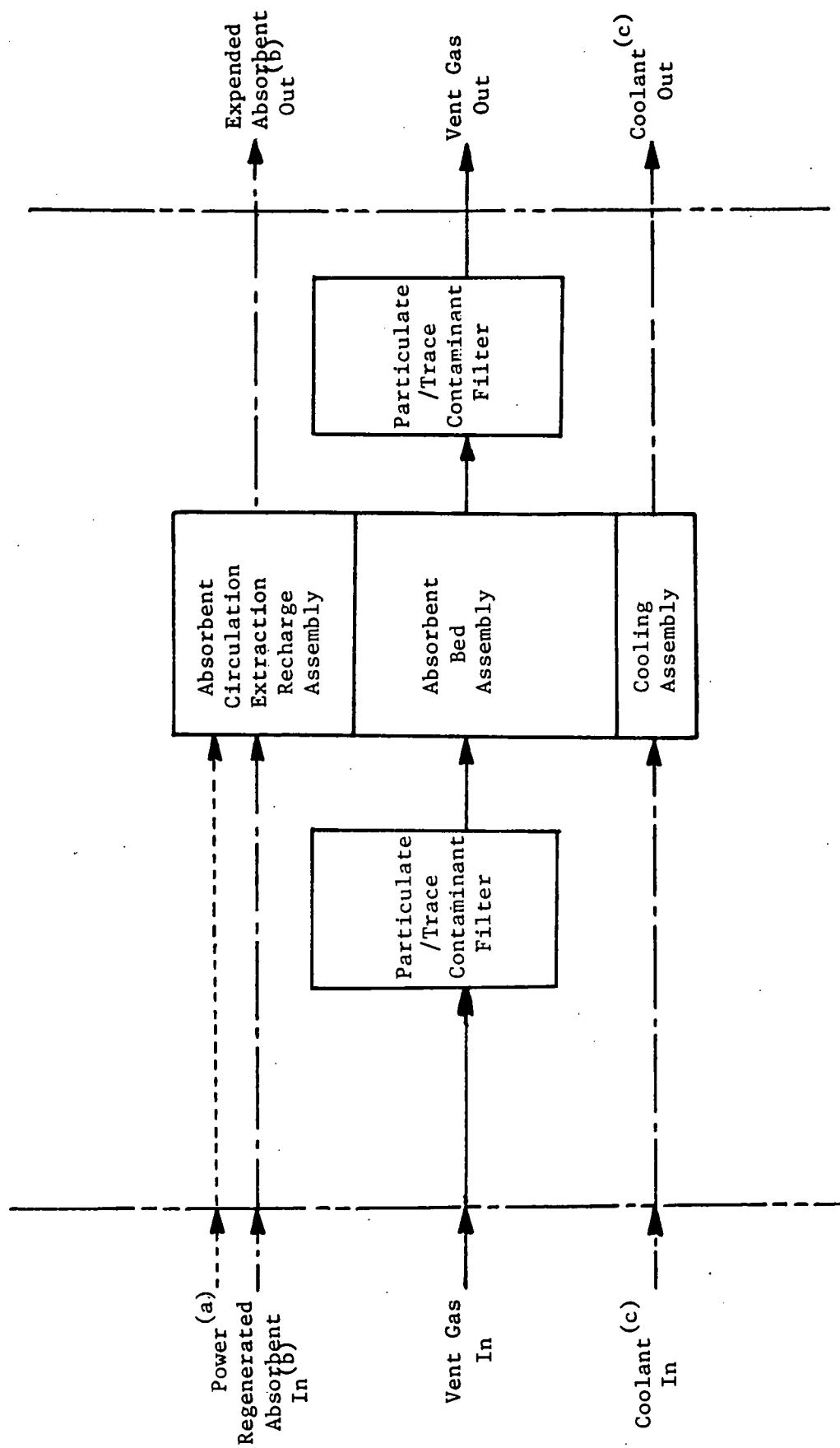


FIGURE 11 ABSORBER MODULE TEMPERATURE RISE WITH PASSIVE COOLING



(a) Heat Load = 61 W (207 Btu/hr assuming CO₂ conversion to CO₃²⁻).

FIGURE 12 ABSORBER MODULE MASS AND ENERGY BALANCE



- (a) Not needed in Stationary Absorbent design.
- (b) Capped during EVA.
- (c) Not needed with passive thermal control.

FIGURE 13 FUNCTIONAL BLOCK DIAGRAM OF ABSORBER MODULE

simultaneous feed for H_2 and expended absorbent to the anode compartment. Problems were experienced during operation in getting the two-phase reactant mixture to the electrode surface for the desired reactions to occur. As a result, the regenerator configuration and regeneration mechanism were changed to eliminate the need for hydrogen feed. In the current configuration, only the expended absorbent is fed to the anode compartment.

Design Requirements

The design capacity of the Electrochemical Regenerator is based on meeting the annual 2,000-hour EVA requirement. Its design performance is given in Table 4.

The regeneration of the expended absorbent involves the elimination of CO_2 and moisture from the carbonate and bicarbonate ions of the absorption reaction and also generation of hydroxyl ions at the same time. Electrochemical half cell reactions for anode, $CO_3^{2-} \rightarrow CO_2 + 1/2 O_2 + 2e^-$ and $2HCO_3^- \rightarrow 2CO_2 + 1/2 O_2 + H_2O + 2e^-$ and for cathode, $2H_2O + 2e^- \rightarrow 2OH^- + H_2$ can be used for the regeneration of this expended absorbent. Figure 14 shows the mechanisms involved in the process.

Electrochemical Regenerator Cell Design

The functional schematic of an Electrochemical Regenerator cell is shown in Figure 15. Expended absorbent enters the feed compartment and a portion of the absorbent feed flows across the electrode assembly. The CO_2 and O_2 evolved at the anode exits the cell with circulating expended absorbent. The H_2 produced at the cathode exits the cell with regenerated absorbent.

The cell frame design is very similar to that of the Life Systems' three-compartment Static Feed Electrolyzer (SFE).

A unitized cell core consists of an anode, a cathode and an electrolyte matrix bonded together at their edges by a fiberglass/epoxy rim. The anode is of a gas diffusion type and water electrolysis cell electrodes are used as the cathode in the regenerator cell. The active electrode area of a regenerator cell is 232 cm^2 (0.25 ft^2). Its overall dimension is $23.2 \text{ cm W} \times 32.9 \text{ cm H} \times 0.76 \text{ cm thick}$ ($9.15 \text{ in} \times 12.95 \text{ in} \times 0.30 \text{ in}$).

Electrochemical Regenerator Assembly

The Electrochemical Regenerator assembly, which is capable of regenerating the expended absorbent from the absorber module in 10 hours, consists of fourteen 232 cm^2 (0.25 ft^2) regenerator cells, two polysulfone insulation plates and two polysulfone end plates. It also has an interface plate with six tubing inserts for the fluids inlets and outlets. Its overall dimension is $25.4 \text{ cm W} \times 33.5 \text{ cm H} \times 24.1 \text{ cm L}$ ($10.0 \text{ in} \times 13.2 \text{ in} \times 9.5 \text{ in}$). An orthographic view of the regenerator assembly is shown in Figure 16.

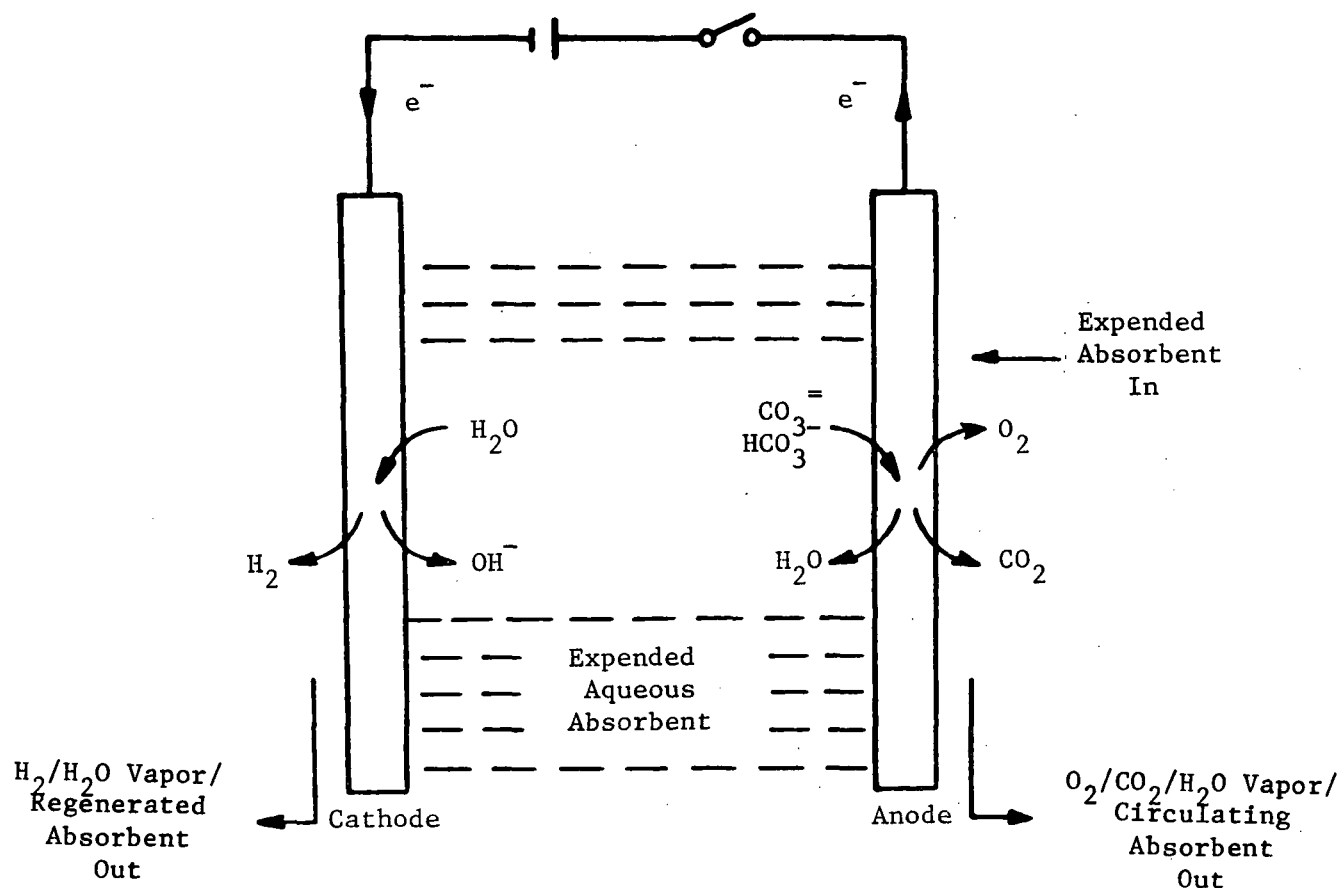
TEST PROGRAM ACTIVITIES

The testing activities of this program were directed toward the demonstration of the breadboard Absorber Module and Electrochemical Regenerator performances. Test stands were used to perform the tests.

TABLE 4 ELECTROCHEMICAL REGENERATOR DESIGN PERFORMANCE

Regeneration Time, hr	10
Absorbent Regeneration Rate, cm ³ /min (cfm)	10.2 ^(a) (0.00036)
CO ₂ Evolution Rate, Average, kg/hr (lb/hr)	0.045 (0.100)
O ₂ Evolution Rate, kg/hr (lb/hr)	0.046 (0.102)
H ₂ Evolution Rate, kg/hr (lb/hr)	0.006 (0.013)
Coolant	
Type	Absorbent
Flow Rate, kg/hr (lb/hr)	11 (24)
Temperature, K (F)	300-344 (80-160)
Electrochemical Cell	
Voltage, V	1.90-2.20
Current Density, mA/cm ² (ASF)	108 (100)
Total Active Area, cm ² (ft ²)	3,214 (3.46)
Temperature, K (F)	322 (120)
Pressure, kPa (psia)	106 (15.5)
Anode-to-Cathode Delta P, kPa (psid)	3.4 (0.5)
Gravity	0-1

(a) Based on regeneration of the absorbent in the Absorber Module in 10 hr.



H₂O Vaporization: H₂O Liquid in Absorbent → H₂O Vapor in Product Gases

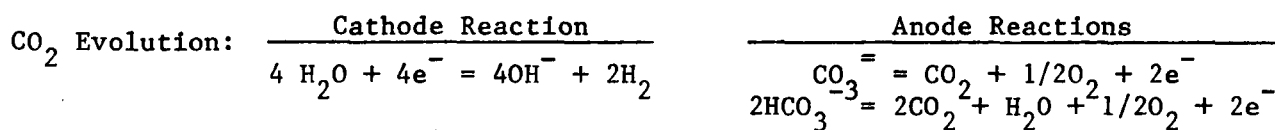


FIGURE 14 ELECTROCHEMICAL REGENERATION MECHANISM

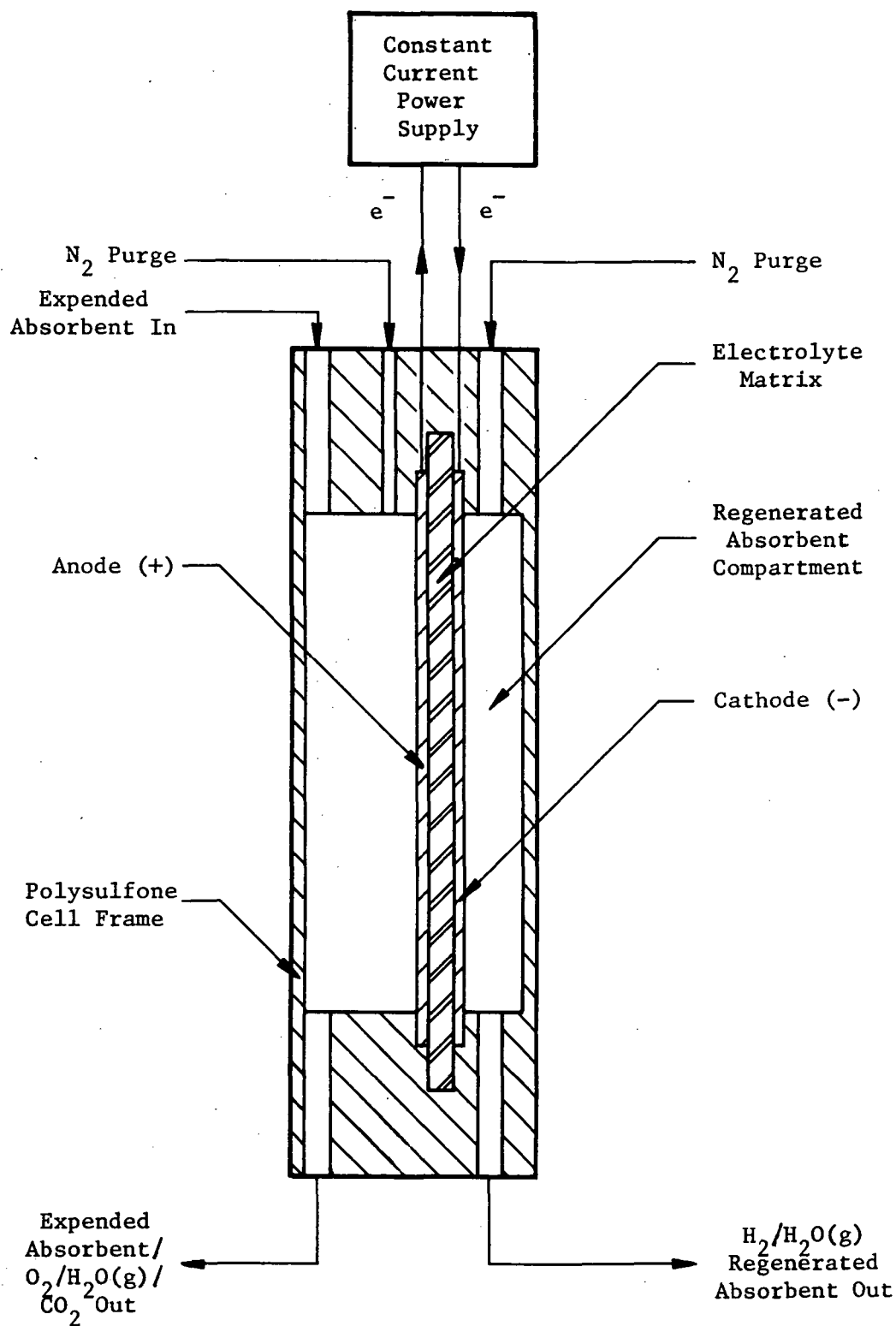


FIGURE 15 ELECTROCHEMICAL REGENERATOR CELL FUNCTIONAL SCHEMATIC

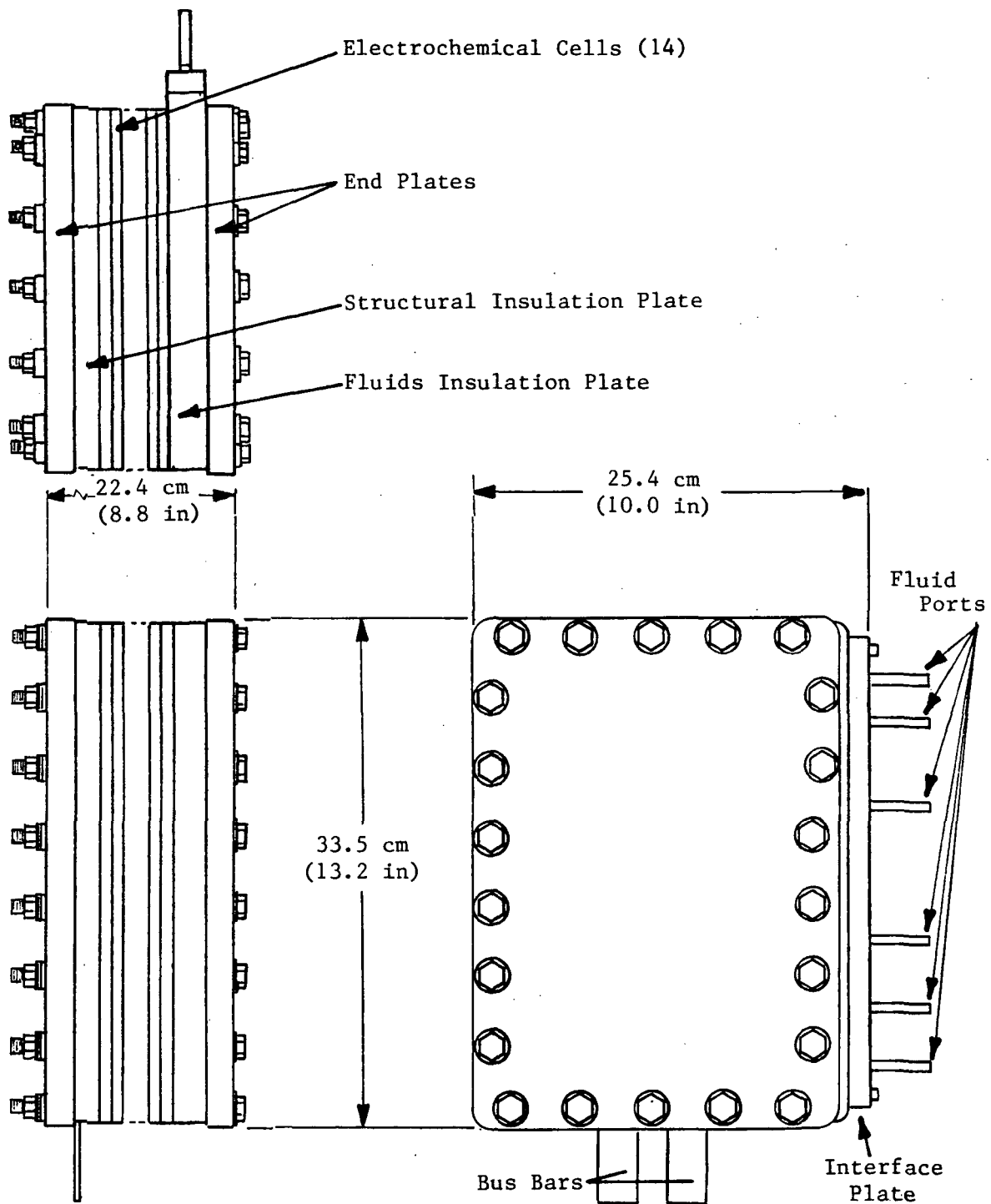


FIGURE 16 ORTHOGRAPHIC VIEWS OF ELECTROCHEMICAL REGENERATOR

Absorber Module Testing

Tests were conducted with the Absorber Module in an experimental test stand. The objectives of these tests were to determine the performance of the module at various operation conditions, including vent gas pressure, CO_2 partial pressure, flow rates and temperature. The effects of absorbent circulation on the absorption rate and absorbent utilization were characterized also. The following is the description of the test hardware and the test results.

Test Stand and Operation

The function of the Absorber Module Test Stand is to provide all process fluid requirements at desired conditions and control and monitor their properties for characterizing the performance of the module and verifying its design. The test stand's design specifications are listed in Table 5.

The mechanical schematic and the pictures of the module and the test stand are shown in Figures 17, 18 and 19. Flow rates of CO_2 , O_2 and nitrogen (N_2) or air are adjusted by flowmeter/controllers. The gas mixture enters the gas humidifier, where the pressure and temperature are controlled by a pressure regulator and a heater, respectively, to provide the gas mixture with required moisture content.

The pressure and temperature of the gas mixture are further adjusted by a pressure regulator and a heat exchanger before the gas enters the module. The flow rate of the vent gas supply and the pressures, temperatures, dew points of the module inlet and outlet gas streams are monitored. A vacuum pump is used for operating the module at subatmospheric pressures.

Small portions of the inlet and outlet vent gas streams are sent to CO_2 analysis equipment. The mechanical schematic and the picture of the CO_2 analysis setup are shown in Figures 20 and 21.

Test Results

The Absorber Module was tested at the conditions shown in Table 6 for Run No. 1. The test was continued for 5 hours at an inlet pCO_2 of 0.28 kPa (2.1 mm Hg) and an additional 1.5 hours at an inlet pCO_2 of 0.52 kPa (3.9 mm Hg). The CO_2 absorption performance is presented in Figure 22. In general, the CO_2 absorption efficiency remained above 92% throughout the run (including both low and high pCO_2 operation). The Absorber Module thus performed very well, with no reduction in absorption efficiency through the entire run. It is believed that the residual CO_2 level in the vent gas outlet is due primarily to vent gas bypassing the membrane bed, thus not having any of its CO_2 removed. Complete elimination of the vent gas bypassing should result in much less residual CO_2 being observed in the outlet vent gas.

A second Absorber Module test run was performed following recharge of fresh absorbent. The operating conditions for this run are also shown in Table 6 (Run No. 2). The test was continued for 8.5 hours at an inlet pCO_2 of

TABLE 5 ABSORBER MODULE TEST STAND SPECIFICATIONS

Vent Gas Composition	N ₂ /O ₂ /CO ₂ /H ₂ O vapor
Vent Gas Flow Rate, acdm (acfm)	
Nominal	170 (6.0)
Range	99-269 (3.5-9.5)
Vent Gas Temperature, K (F)	
Nominal	297 (75)
Range	289-305 (60-89)
Vent Gas Relative Humidity, %	
Nominal	90
Range	40-100
Vent Gas Dew Point Temperature, K (F)	
Nominal	295.6 (72)
Range	281-301 (45-82)
CO ₂ Absorption Rate, kg/hr (lb/hr)	
Nominal	0.093 (0.20)
Range	0.32-0.54 (0.06-0.40)
Module Inlet CO ₂ Partial Pressure, Pa (mm Hg)	
Nominal	507 (3.8)
Range	227-1, 332 (1.7-10.0)
System Pressure, kPa (psia)	
Nominal	55.2 (8.0)
Range	41-101 (6.0-14.7)
Coolant Type	Water
Coolant Flow Rate, kg/hr (lb/hr)	
Nominal	9.1 (20)
Range	TBD
Coolant Temperature, K (F)	
Nominal	294 (70)
Range	289-301 (60-82)
Coolant Pressure Drop, Maximum, kPa (psid)	20.7 (3.0)
Power Supply	110 V, AC, 60 Hz, 1Ø

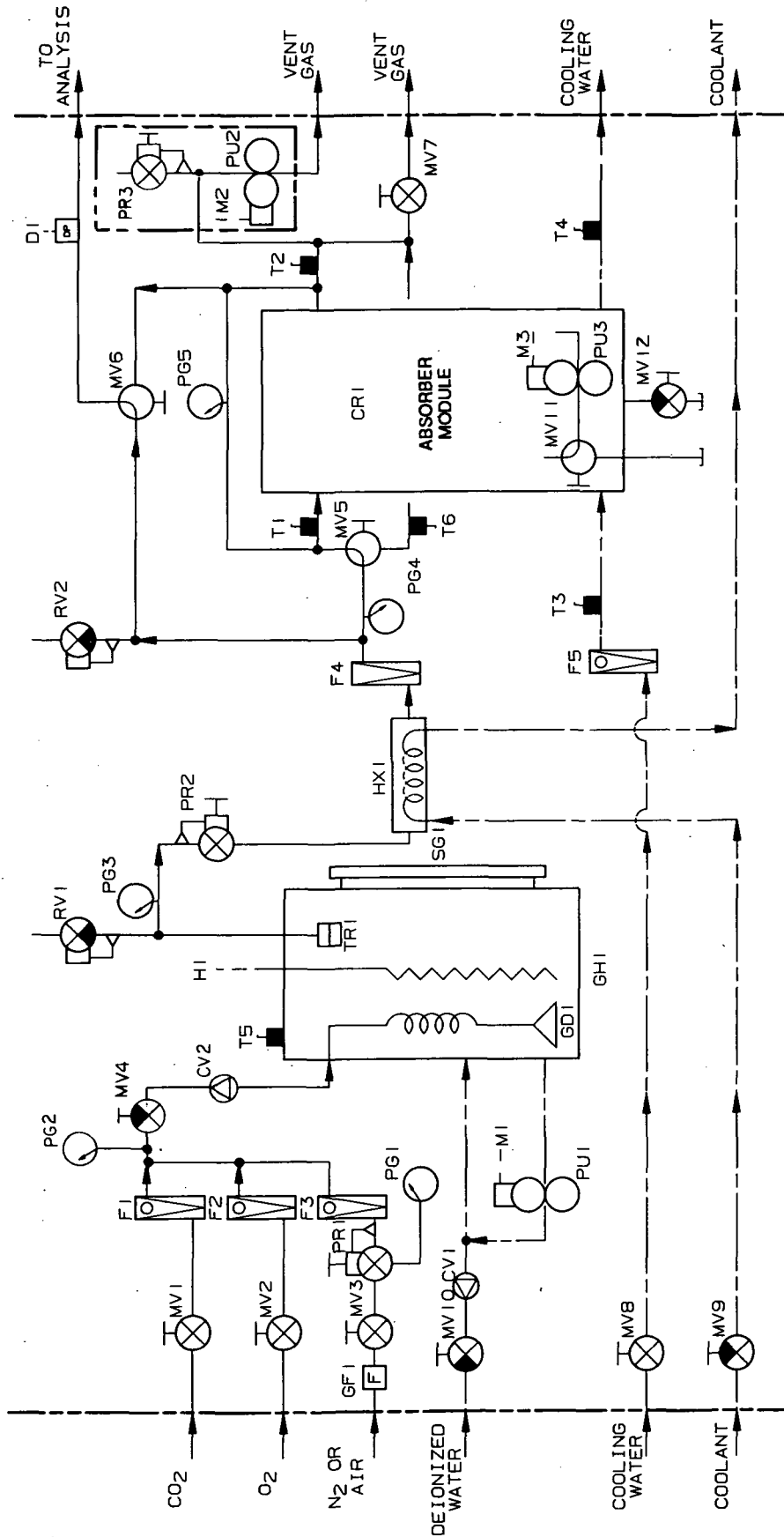


FIGURE 17 ABSORBER MODULE TEST STAND MECHANICAL SCHEMATIC WITH SENSORS

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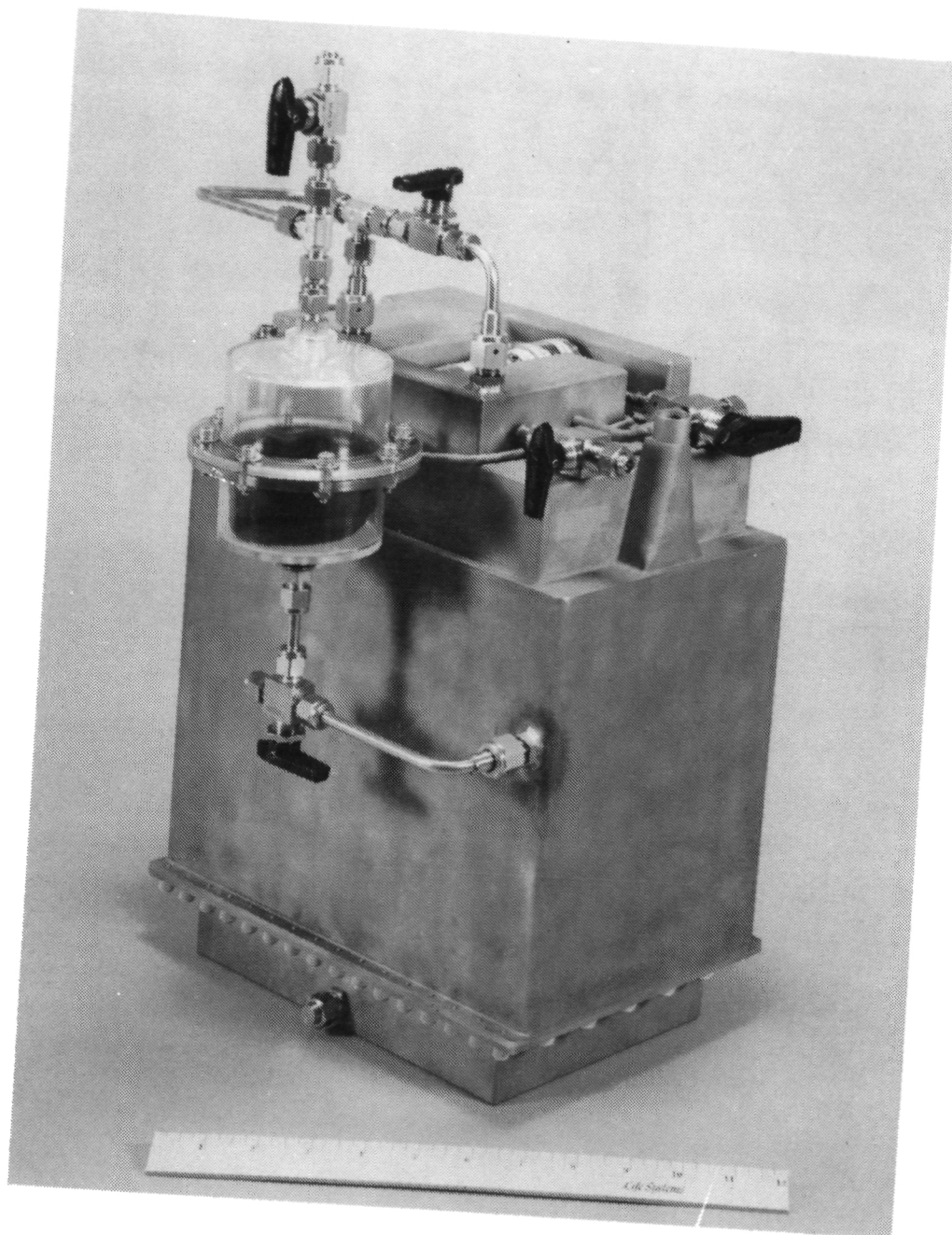


FIGURE 18 ABSORBER MODULE (BREADBOARD)

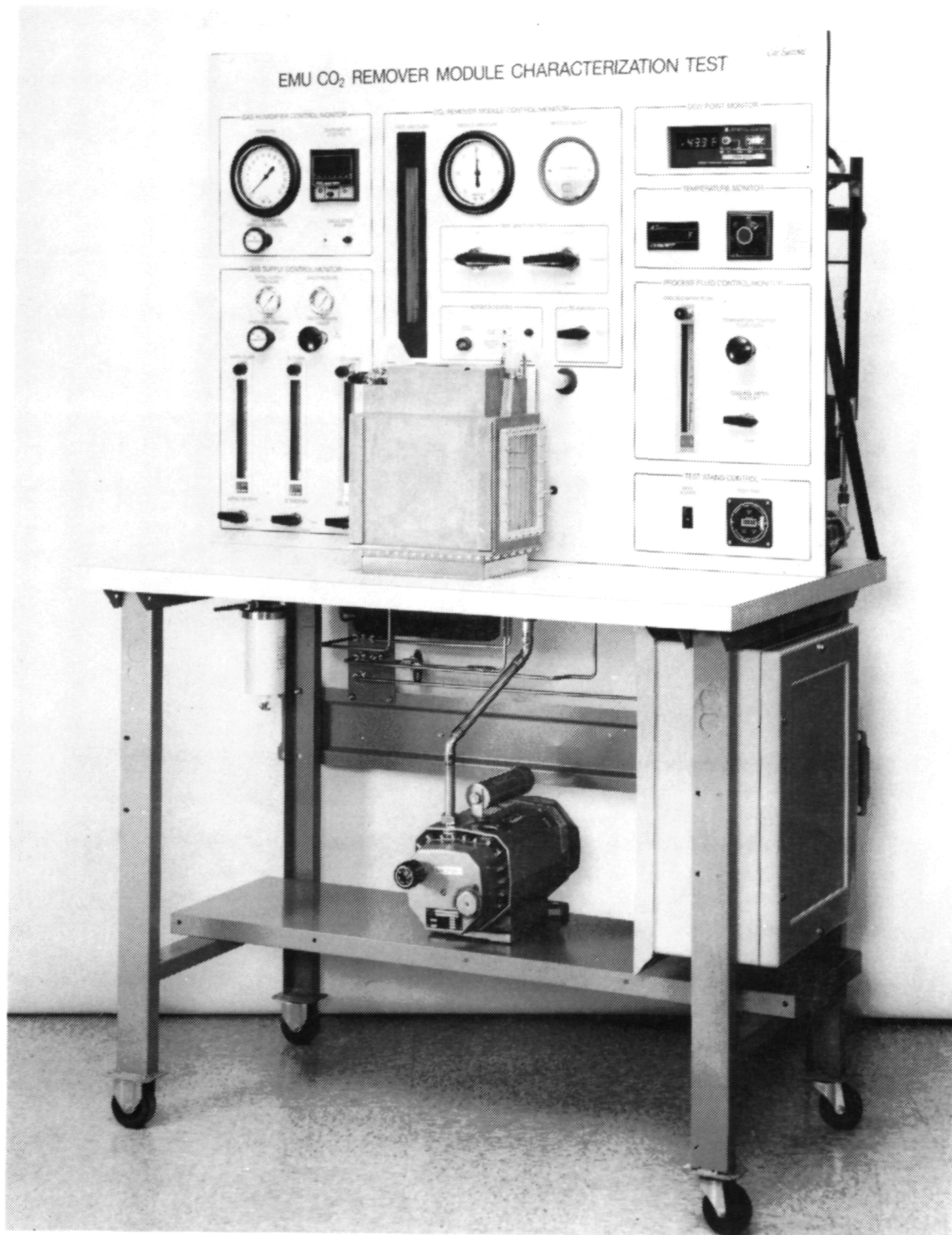


FIGURE 19 ABSORBER MODULE TEST STAND

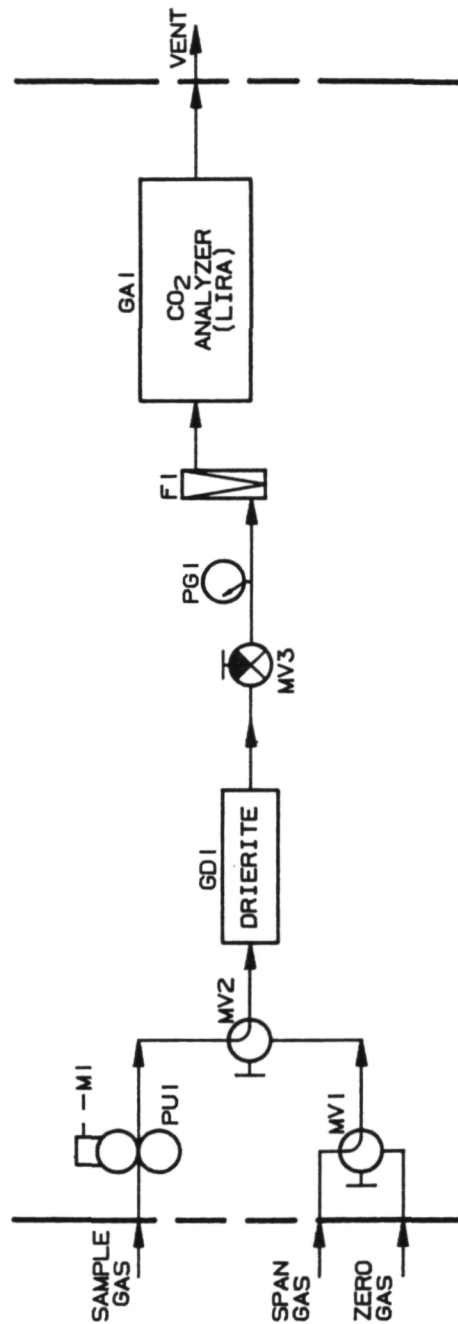


FIGURE 20 VENT GAS CO₂ ANALYSIS SETUP MECHANICAL SCHEMATIC

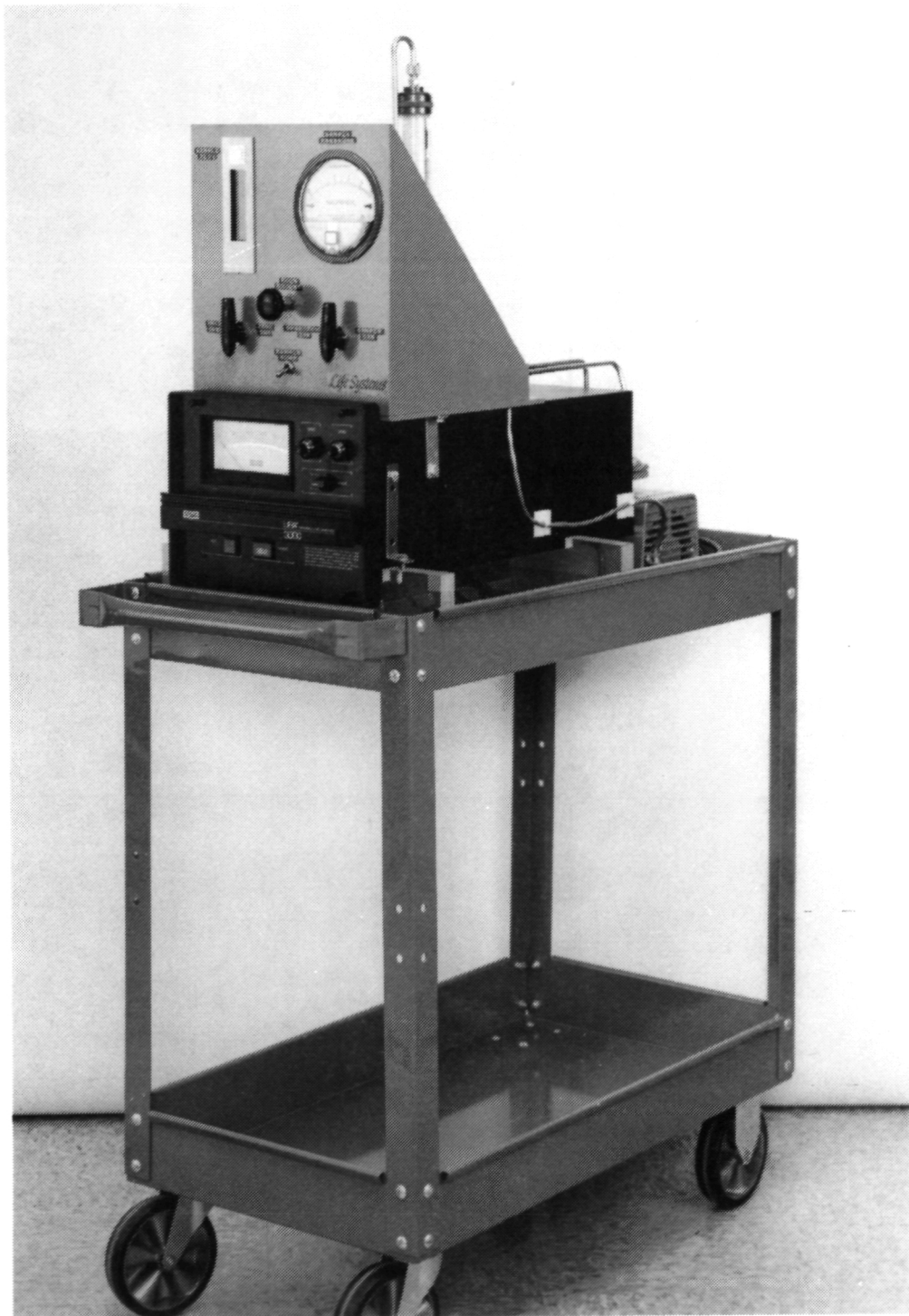


FIGURE 21 CO₂ ANALYSIS TEST SETUP

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TABLE 6 ABSORBER MODULE OPERATING CONDITIONS

Condition	Run No. 1	Run No. 2	Run No. 3	Run No. 4
Vent Gas Flow, dm ³ /min (acfm)	170 (6.0)	170 (6.0)	170 (6.0)	170 (6.0)
Module Pressure, kPa (psia)	55 (8.0)	55 (8.0)	101 (14.7)	55 (8.0)
Vent Gas Temperature, K (F)	293-297 (68-74)	299-302 (79-83)	301-307 (82-93)	297-299 (75-79)
Vent Gas Dew Point, K (F)	285 (53)	289 (61)	289 (60)	290-294 (62-70)
Vent Gas Inlet pCO ₂ , kPa (mm Hg)	0.28-0.52 (2.1-3.9) ^(a)	0.52 (3.9)	0.52-1.33 (3.9-10.0) ^(b)	0.52 (3.9)
Absorbent Circulation, cc/min (gpm)	125 (0.033)	125 (0.033)	125 (0.033)	125 (0.033)
Absorbent Concentration, %wt KOH	30	30	30	45

(a) Vent gas pCO₂ during Run No. 1 was 0.28 kPa (2.1 mm Hg) for first 5 hr and 0.52 kPa (3.9 mm Hg) for additional 1.5 hr.

(b) At pCO₂ = 1.33 kPa (10.0 mm Hg) for 25 min during the run.

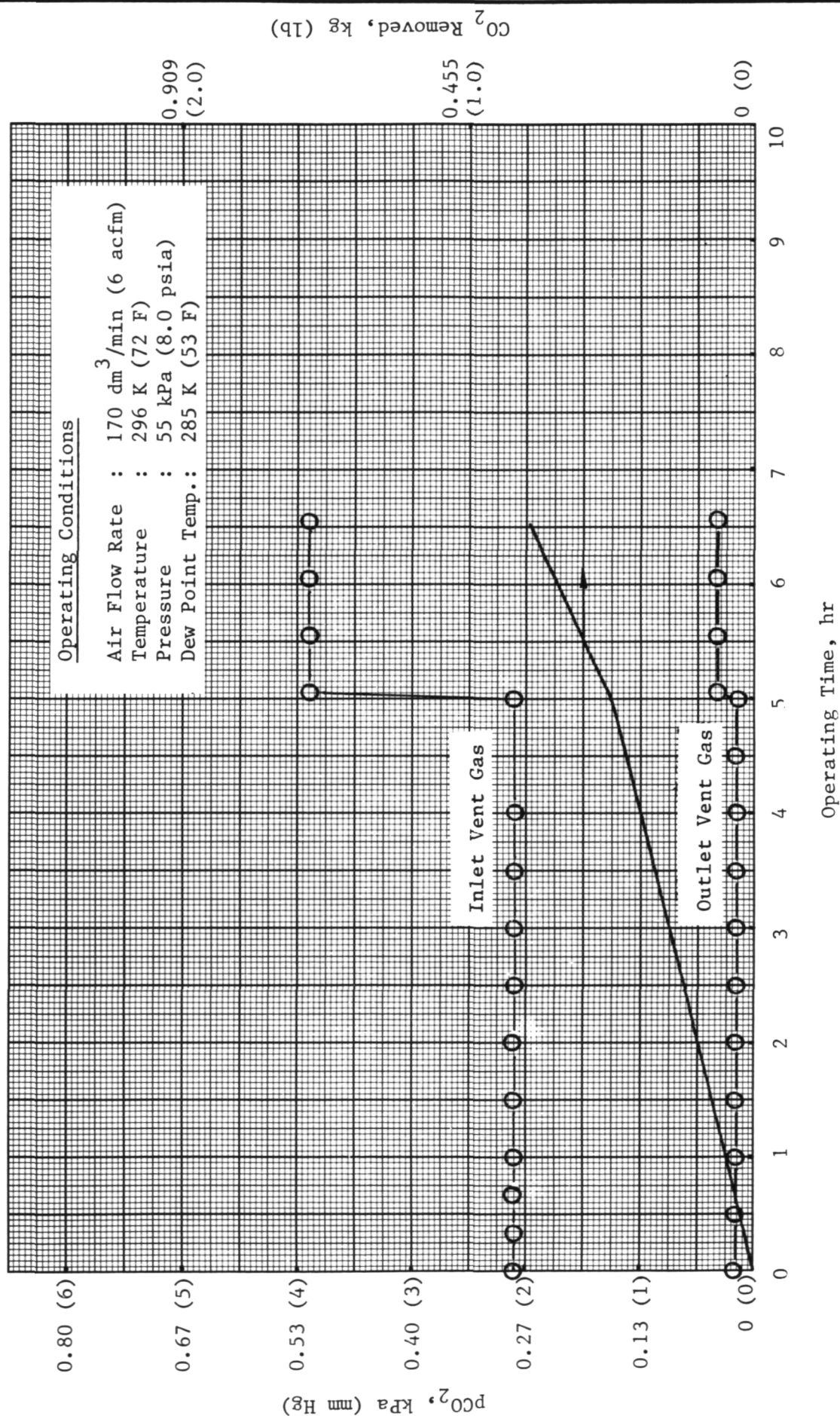


FIGURE 22 ERCA CO₂ REMOVAL PERFORMANCE - RUN NO. 1

0.52 kPa (3.9 mm Hg). The CO₂ removal efficiency remained above 93% through the first 6.0 hours of testing and was still above 84% by the end of the run. The CO₂ absorption results are shown in Figure 23. Again, the CO₂ absorption performance was very good, with the system removing CO₂ for much longer than the designed operating time of 5.0 hours.

During both of the above tests, a slight amount of absorbent leakage in the outlet vent gas header was seen through the window. The leakage rate is low enough that it should not have any significant effect on the CO₂ absorption test results. The small amount of vent gas bypassing (believed to be approximately 6% to 8% of the total inlet vent gas flow) prohibited accurate determination of the maximum CO₂ absorption efficiency.

Another CO₂ removal performance test was run with baseline absorbent at the conditions shown below:

Vent Gas Flow Rate	: 170 dm ³ /min (6 acfm)
Temperature	: 301 ~ 307 K (82 ~ 93 F)
Pressure	: 101.3 kPa (14.7 psia)
Dew Point Temp. Inlet:	289 ~ 292 K (60 ~ 65 F)

The inlet partial pressure of CO₂ was maintained at 0.51 kPa (3.85 mm Hg) for the first 3 hours and 36 minutes. During this period the outlet pCO₂ remained constant at 0.10 kPa (0.75 mm Hg). The test result is shown in Figure 24. This represents 80.5% removal of incoming CO₂, which is not as high as in the two previous runs of over 95% removal at 55 kPa (8 psia). This difference is believed to be due to increased vent gas by passing caused by less effective module sealing, rather than to a difference between high and low pressure Absorber Module performances.

After 3 hours and 36 minutes at a pCO₂ of 0.51 kPa (3.85 mm Hg) at the inlet, pCO₂ was raised to 1.33 kPa (10 mm Hg) to observe the difference in performance. As shown in Figure 25, the outlet pCO₂ increased to 0.23 kPa (1.75 mm Hg), which represents 82.5% CO₂ removal. This also means that in spite of bypassing, the module removed CO₂ at the rate of 0.20 kg/hr (0.43 lb/hr), which is higher than the maximum CO₂ absorption rate of 0.18 kg/hr (0.40 lb/hr) required by the design specifications.

After about 25 minutes at 1.33 kPa (10 mm Hg), the inlet pCO₂ was lowered to 0.52 kPa (3.9 mm Hg), which caused the outlet pCO₂ to return to 0.093 kPa (0.70 mm Hg). This lasted up to the fifth hour when the outlet pCO₂ started to gradually rise.

Although the Absorber Module was not designed for the absorption of metabolic moisture from the vent gas, it was believed that the module had the capability to do so. Run No. 4 was made to verify the simultaneous absorption of vent gas CO₂ and moisture by the absorber module. An absorbent higher in concentration than the baseline absorbent was used.

The test conditions are shown in Table 6 and results are shown in Figure 26. As can be seen in the figure, outlet vent gas water vapor pressures are very

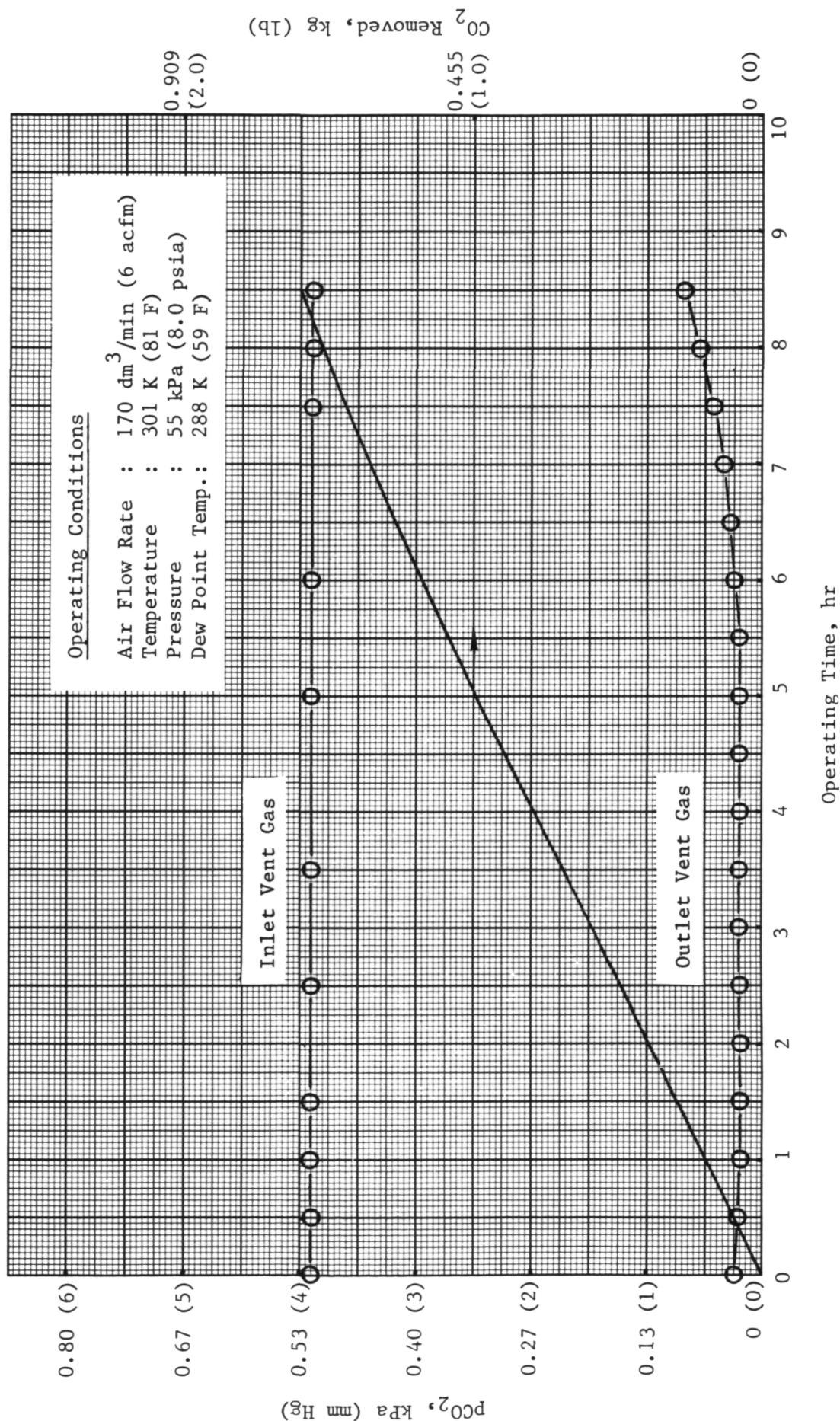


FIGURE 23 ERCA CO₂ REMOVAL PERFORMANCE - RUN NO. 2

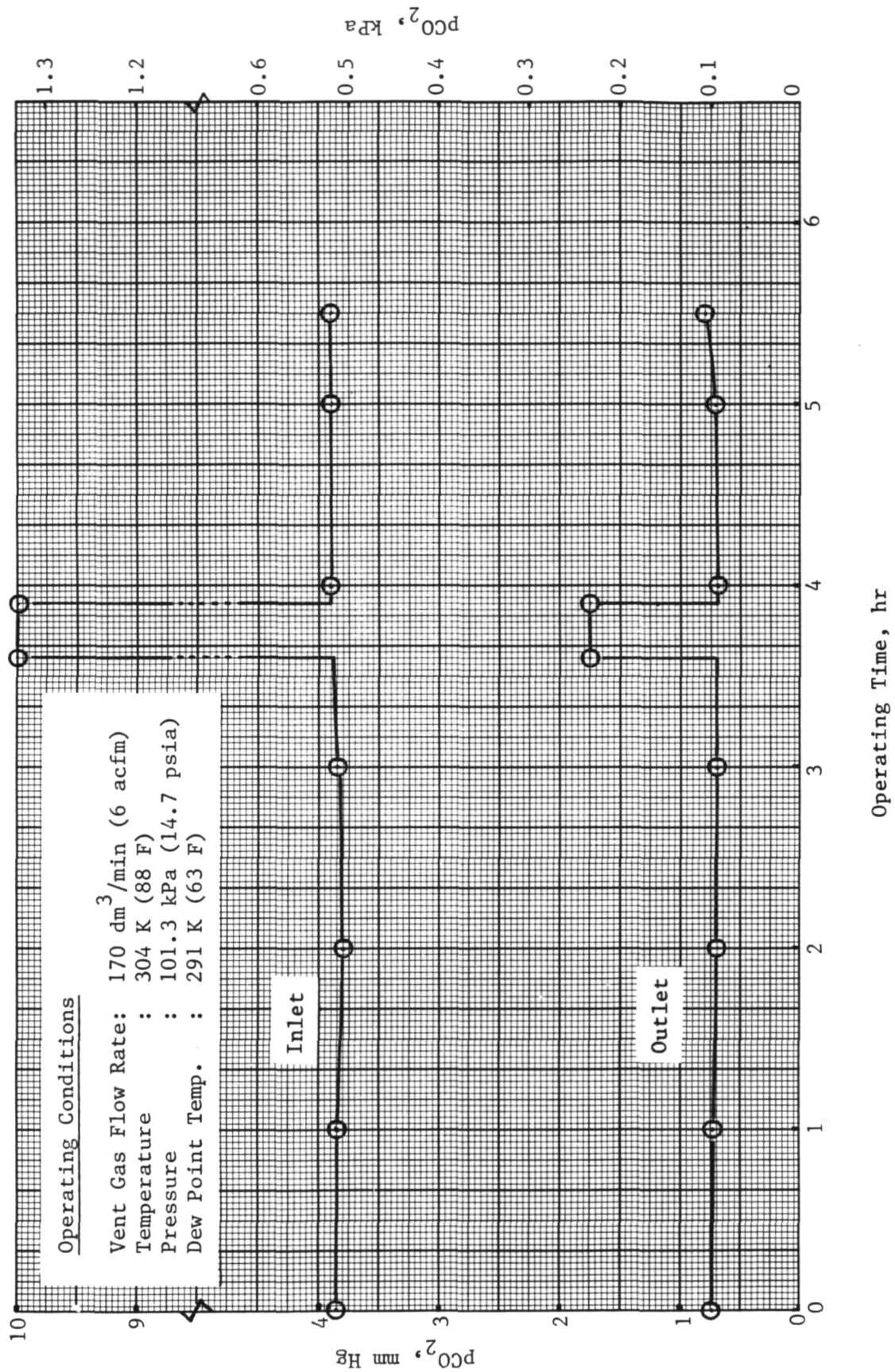


FIGURE 24 ERCA CO₂ REMOVAL PERFORMANCE - RUN NO. 3

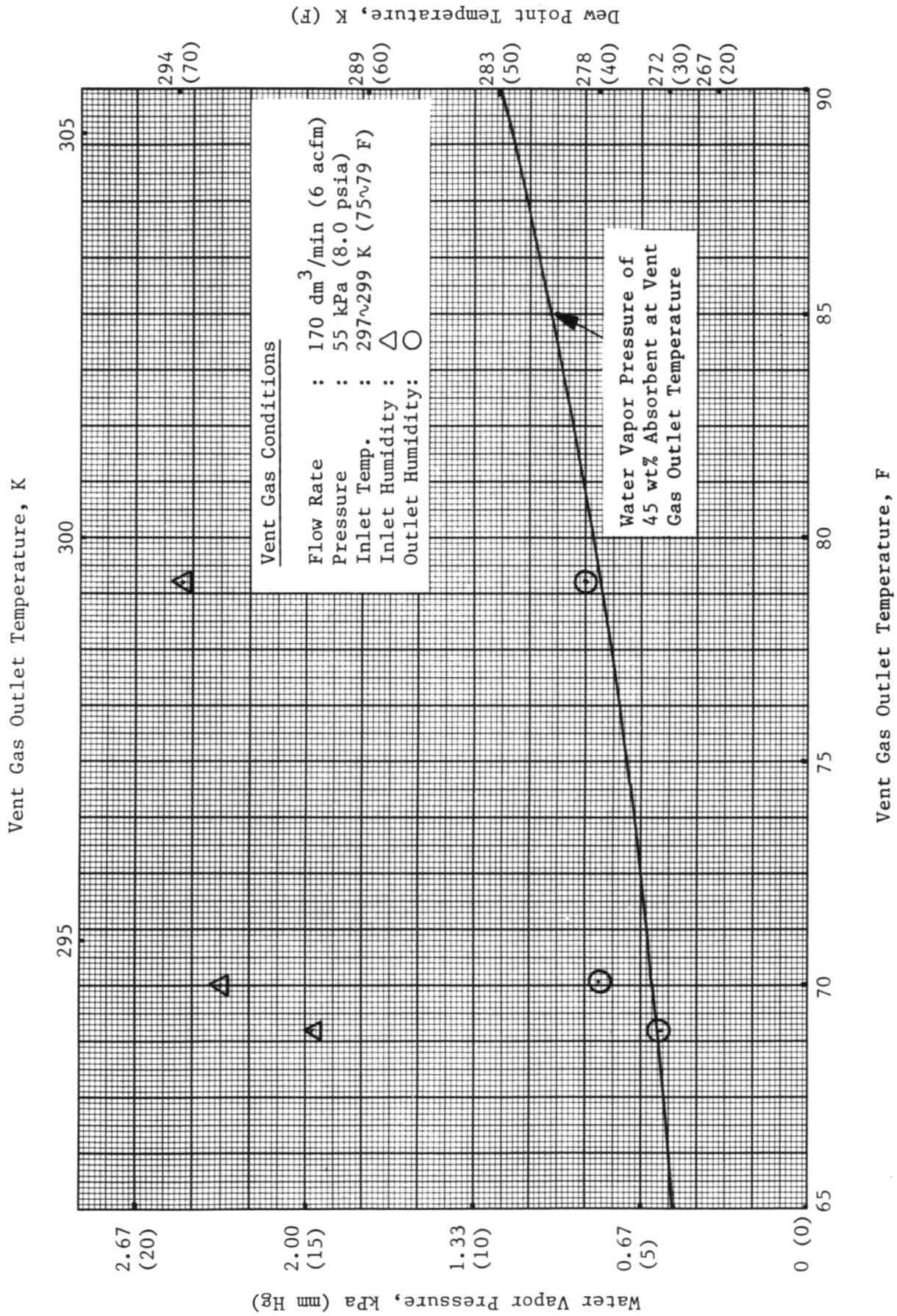


FIGURE 25 MOISTURE REMOVAL PERFORMANCE OF THE ABSORBER MODULE WITH 45 WT% ABSORBENT - RUN NO. 4

close to the equilibrium water vapor pressures of the absorbent. The pairs of inlet and outlet data points at 294 (69), 294 (70) and 299 K (79 F) vent gas outlet temperatures represent the moisture removal rates of 0.10 (0.22), 0.11 (0.24) and 0.12 kg/hr (0.26 lb/hr), respectively.

This figure clearly shows the advantage of using aqueous absorbent in controlling the moisture content of vent gas over using a condensing heat exchanger. For example, when 297 K (75 F) cooling water is used to cool 45 wt% absorbent to 299 K (79 F), the vent gas outlet dew point can be as low as 278 (41 F) whereas a condensing heat exchanger would only be able to lower the dew point to 297 K (75 F) plus a few degrees. This is due to the effect of "vapor pressure depression phenomenon," which was mentioned earlier. The degree of dew point lowering depends on the absorbent concentration and temperature which is shown in Figure 26. The effect of absorbent temperature and concentration on the water removal rate at nominal vent gas conditions is shown in Figure 27.

Run No. 2 for the removal of CO_2 was continued to determine the total CO_2 absorption capacity of the absorber. The results are shown in Figure 28. The level of pCO_2 at the module outlet continued rising for two more hours, then leveled off and went down by 0.03 kPa (0.2 mm Hg) before starting rising again. This phenomenon may have been caused by convective movement of absorbent during overnight standing (the run was shutdown at the 8.5 hour point and restarted the next morning).

By graphical integration, the total amount of CO_2 absorbed was estimated to be approximately 1.05 kg (2.32 lb). Compared to the theoretical CO_2 capacity of the absorbent in the Absorber Module (based on complete conversion of OH^- to $\text{CO}_3^{=}$), 14% more CO_2 was absorbed. This was due to the conversion of $\text{CO}_3^{=}$ into HCO_3^- . This phenomenon was extensively studied by Tosh, et al. Some of his work is shown in Figure 29, which shows that at pCO_2 of 0.51 kPa (3.8 mm Hg) an equilibrium conversion of more than 20% is possible.

Electrochemical Regenerator Testing

A series of experimental tests were conducted with the Electrochemical Regenerator Module to characterize the regeneration of the expended absorbent. The objectives of these tests were to characterize the module in terms of its regeneration efficiency versus current performance, determine the effect of feed pressure and characterize the electrical performance and absorbent production rate.

Test Stand and Operation

The Electrochemical Regenerator Test Stand provides all process fluids and power required for the regeneration of expended absorbent at specified conditions. It also controls and monitors various process conditions to properly characterize the performance of the Electrochemical Regenerator. Its design specifications are listed in Table 7.

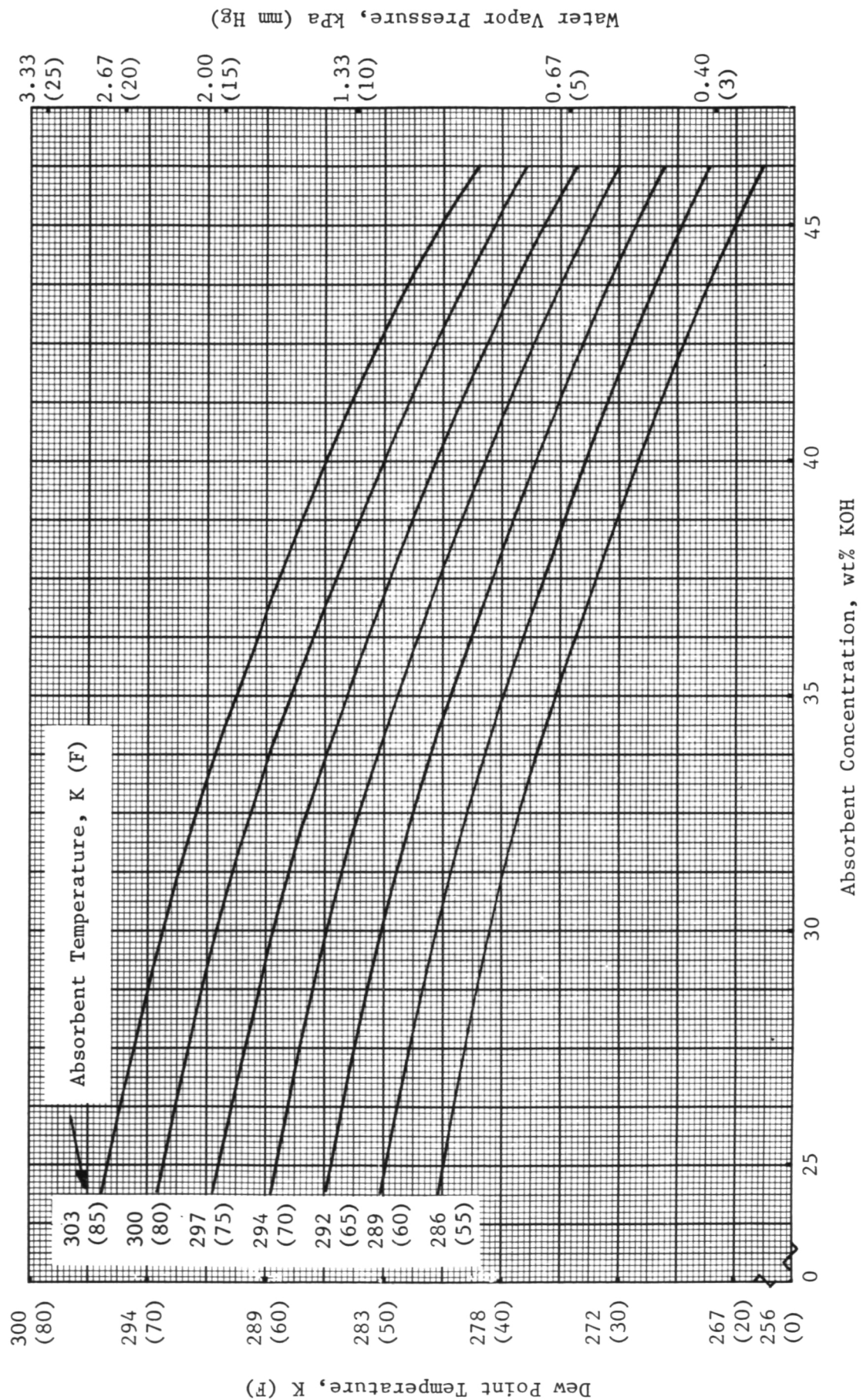


FIGURE 26 VENT GAS DEW POINT TEMPERATURE CHANGE WITH ABSORBENT CONCENTRATION AND TEMPERATURE

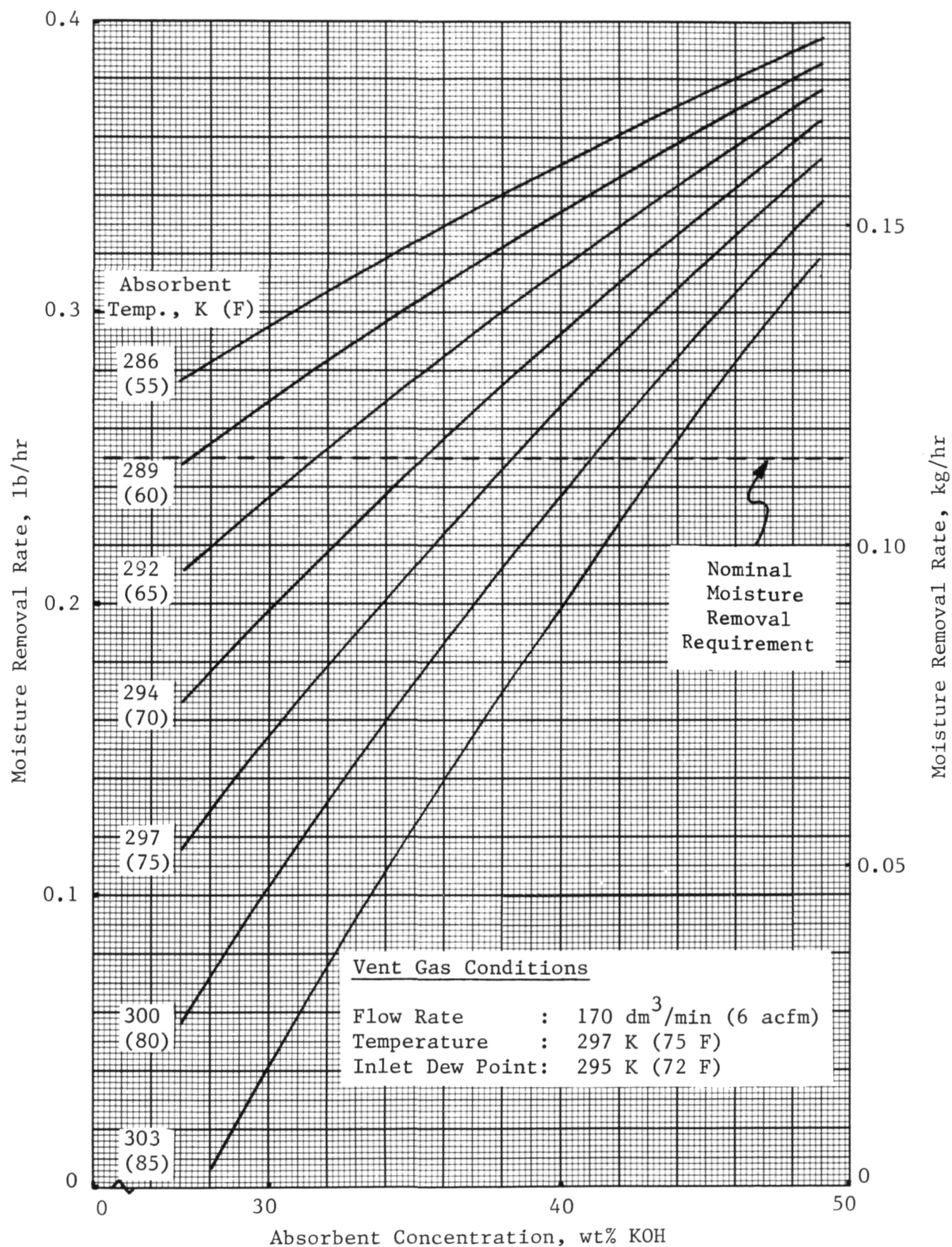


FIGURE 27 ERCA MOISTURE REMOVAL RATES WITH BASELINE ABSORBENT AT VARIOUS ABSORBENT TEMPERATURES

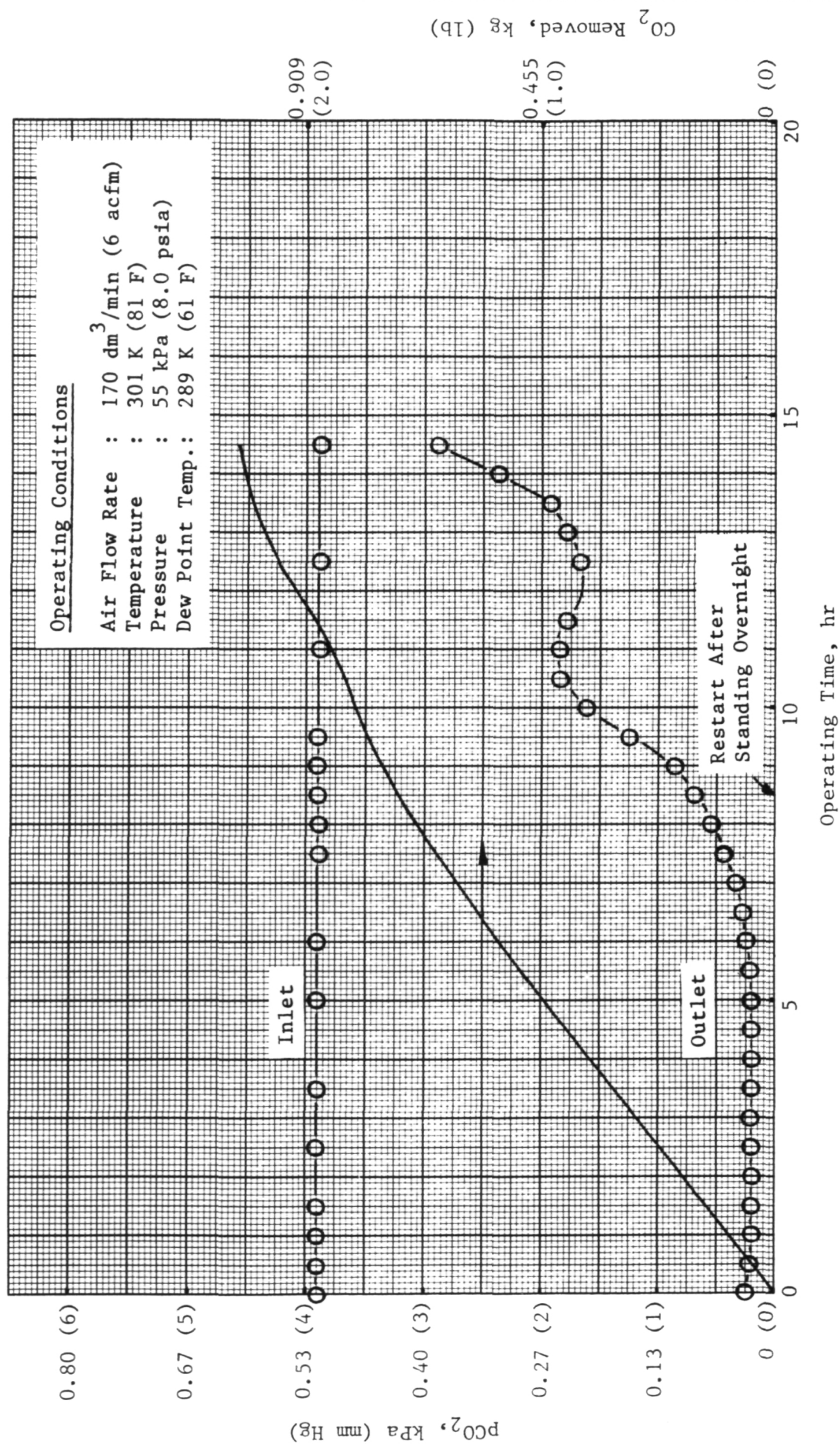


FIGURE 28 ERCA CO₂ REMOVAL PERFORMANCE

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From "Equilibrium Study of the System K_2CO_3 - $KHCO_3$ - CO_2 - H_2O "
by Tosh, et al of the Bureau of Mines³ (1959)

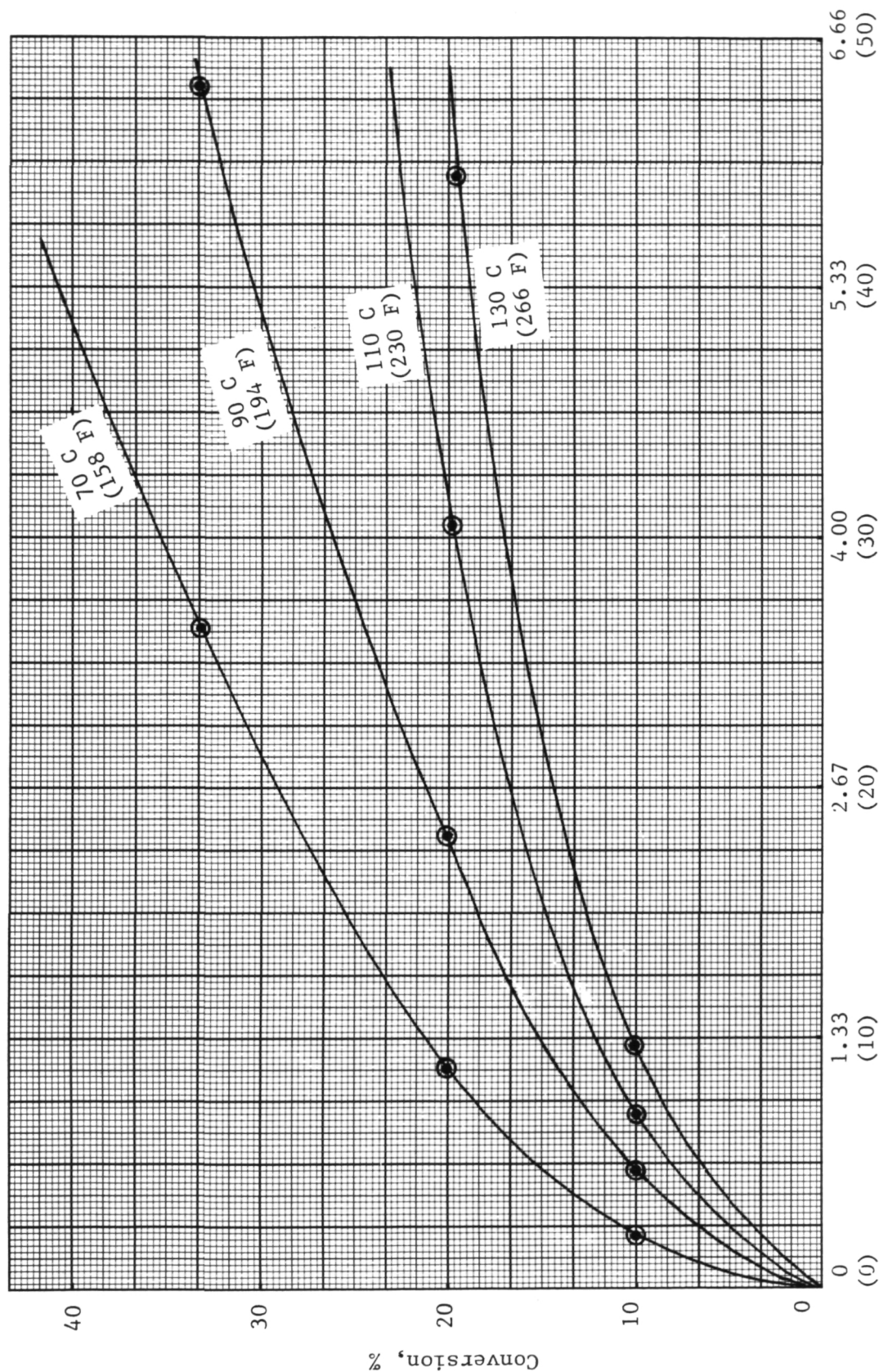


FIGURE 29 EQUILIBRIUM CONVERSION OF 30% K_2CO_3 TO $KHCO_3$ VERSUS CO_2 PARTIAL PRESSURE
CO₂ Partial Pressure, kPa (mm Hg)

TABLE 7 ELECTROCHEMICAL REGENERATOR TEST STAND SPECIFICATIONS

Absorbent Regeneration Rate, Min, cm^3/min (in^3/min)	10.2 (0.62)
CO_2 Evolution Rate, Average, kg/hr (lb/hr)	0.045 (0.10)
O_2 Evolution Rate, kg/hr (lb/hr)	0.046 (0.102)
H_2 Evolution Rate, kg/hr (lb/hr)	0.006 (0.013)
Coolant	
Type	Absorbent
Flow Rate, kg/hr (lb/hr)	11 (24)
Temperature, K (F)	300-344 (80-160)
Purge Gas	
Type	Nitrogen
Pressure, kPa (psia)	310 (45)
Electrochemical Cell	
Voltage, V	1.90 to 2.20
Current Density, mA/cm^2 (ASF)	108 (100)
Total Active Area, cm^2 (ft^2)	3,214 (3.46)
Temperature, K (F)	322 (120)
Pressure, kPa (psia)	106 (15.5)
Anode-to-Cathode Delta P, kPa (psid)	3.4 (0.5)
Power Supply to Regenerator	
Voltage, V	0 to 30
Current, DC, A	0 to 30

The mechanical schematic of the test stand and the pictures of the regenerator and the test stand are shown in Figures 30, 31 and 32. The expended absorbent is supplied by a pump to the feed compartments of the regenerator cells. The pressure, temperature and flow rate of the expended absorbent are controlled for proper cell temperature control and regenerated absorbent production. The pressures of the anode and cathode compartments are adjusted by pressure regulators for proper flow rate of regenerated absorbent. Regenerated absorbent is collected in a tank and periodically analyzed for regeneration efficiency. Product gases are vented or analyzed.

Test Results

Three test runs of the electrochemical regenerator were completed. The first two runs were performed with the feed plate matrix in place and with a total of 10 cells. Prior to the third run, the regenerator module was disassembled. At this time, the feed plate matrix material was removed (the matrix is not required when the regenerator is operated without H_2), and 4 additional cells were installed, bringing the total number of cells to 14.

The operating conditions of the first run are given in Table 8. It is seen that as the current is increased, the regenerated absorbent quality improves (decrease in CO_3 concentration and increase in OH^- concentration). This is shown in Figure 33. The improvement in regenerated absorbent quality that high current provides may not, however, be entirely due to the high current itself, but rather due to the higher absorbent circulation temperatures that result from the high current operation. This temperature effect is also seen in Table 9, with temperature going above the 322 K (120 F) control temperature at higher currents, primarily due to the increased waste heat generation. The proposed benefit of higher absorbent temperature is in reducing the amount of CO_2 reabsorption by the expended absorbent circulating through the anode compartment. Carbon dioxide reabsorption within the anode causes conversion of residual hydroxide in the expended absorbent to carbonate. Further reaction of CO_2 with carbonate to form bicarbonate will also occur. The extent of the bicarbonate formation is dependent on the temperature and pressure conditions within the anode compartment. At higher temperature, less bicarbonate is formed. With absorbent at a lower bicarbonate concentration, the absorbent being supplied for regeneration is at a less expended or less saturated condition. This may allow regeneration efficiency (conversion of CO_3 , HCO_3 to OH^-) to improve.

The operating conditions in Run No. 2, shown in Table 9, lend support to this phenomenon. Once again, the regeneration absorbent quality improves with increasing current, as shown in Figure 34. (This occurs even though the expended absorbent supply is becoming increasingly more spent during the run due to CO_2 reabsorption. This effect is shown in Figure 35.) It is again seen that absorbent temperature increases with increasing current. For the last two data points, which were both at 25 A, there was a temperature difference of 258 K (5 F) in the absorbent temperature. The latter 25 A regenerated absorbent sample, which presumably had a more fully expended absorbent supply (the supply absorbent was not analyzed, but since the data point was taken later in the run it is likely that the absorbent was more expended than in the previous sample) showed a significant improvement in regenerated absorbent quality over the former 25 A sample.

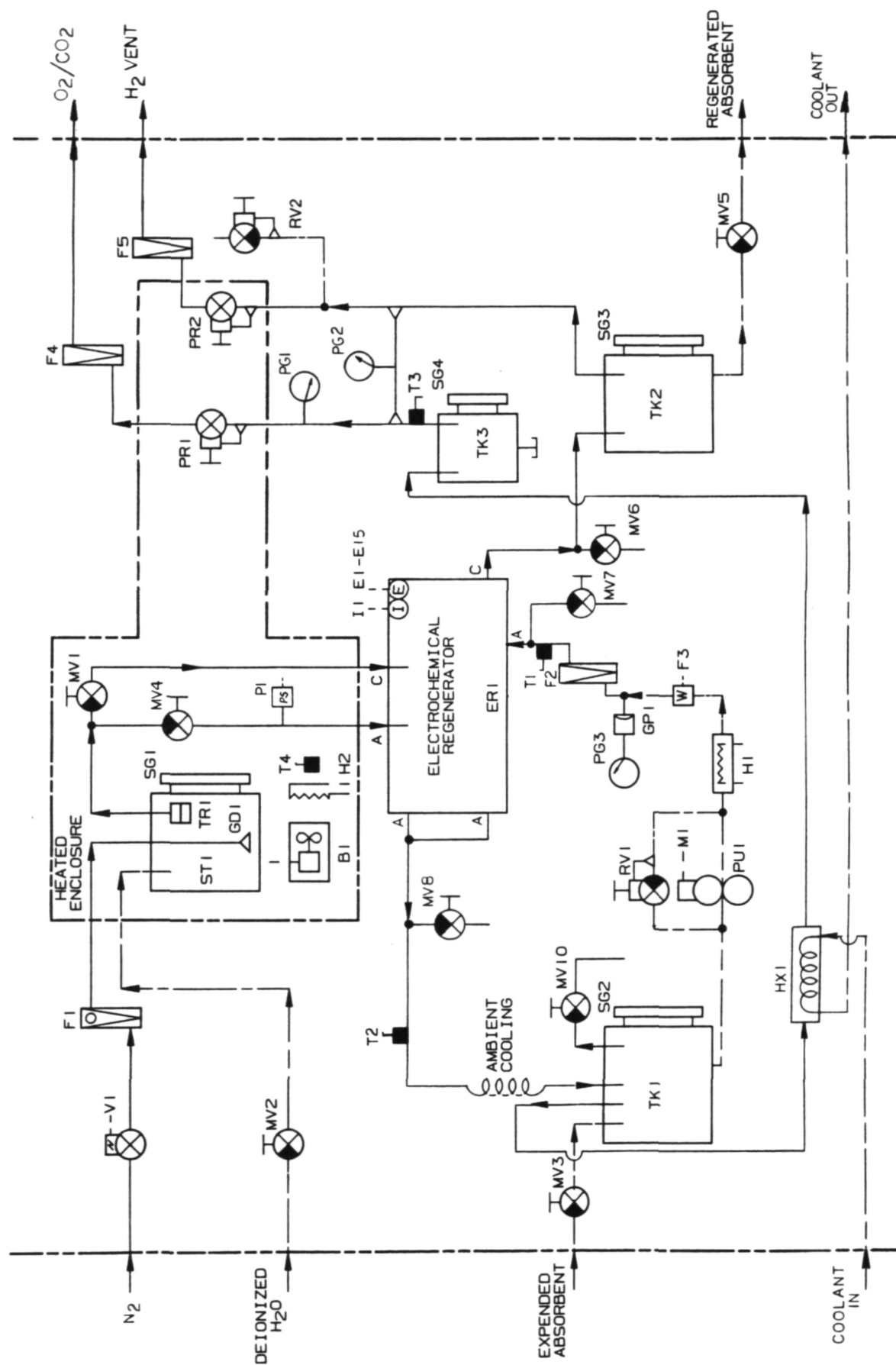


FIGURE 30 ELECTROCHEMICAL REGENERATOR TEST STAND MECHANICAL SCHEMATIC

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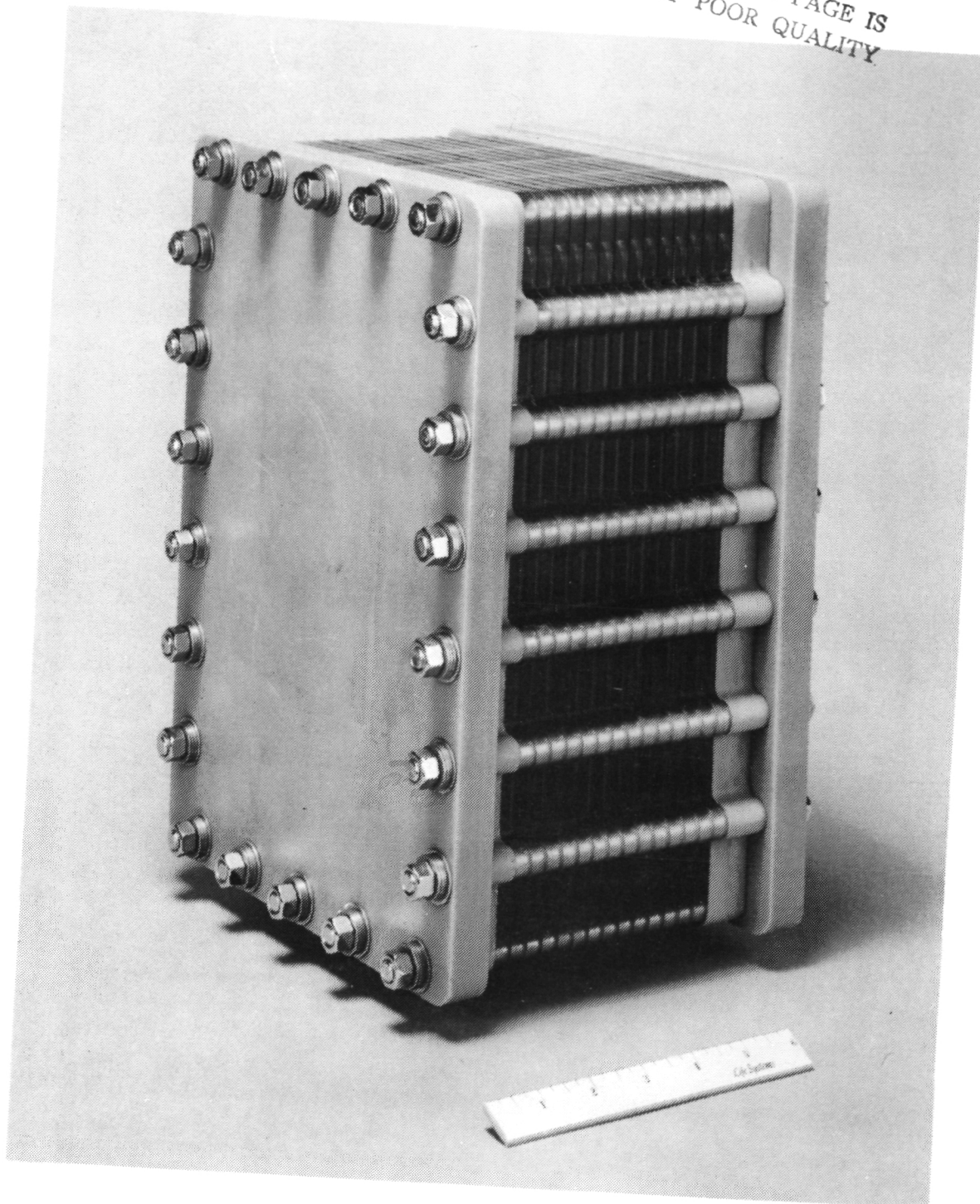


FIGURE 31 ELECTROCHEMICAL REGENERATOR MODULE

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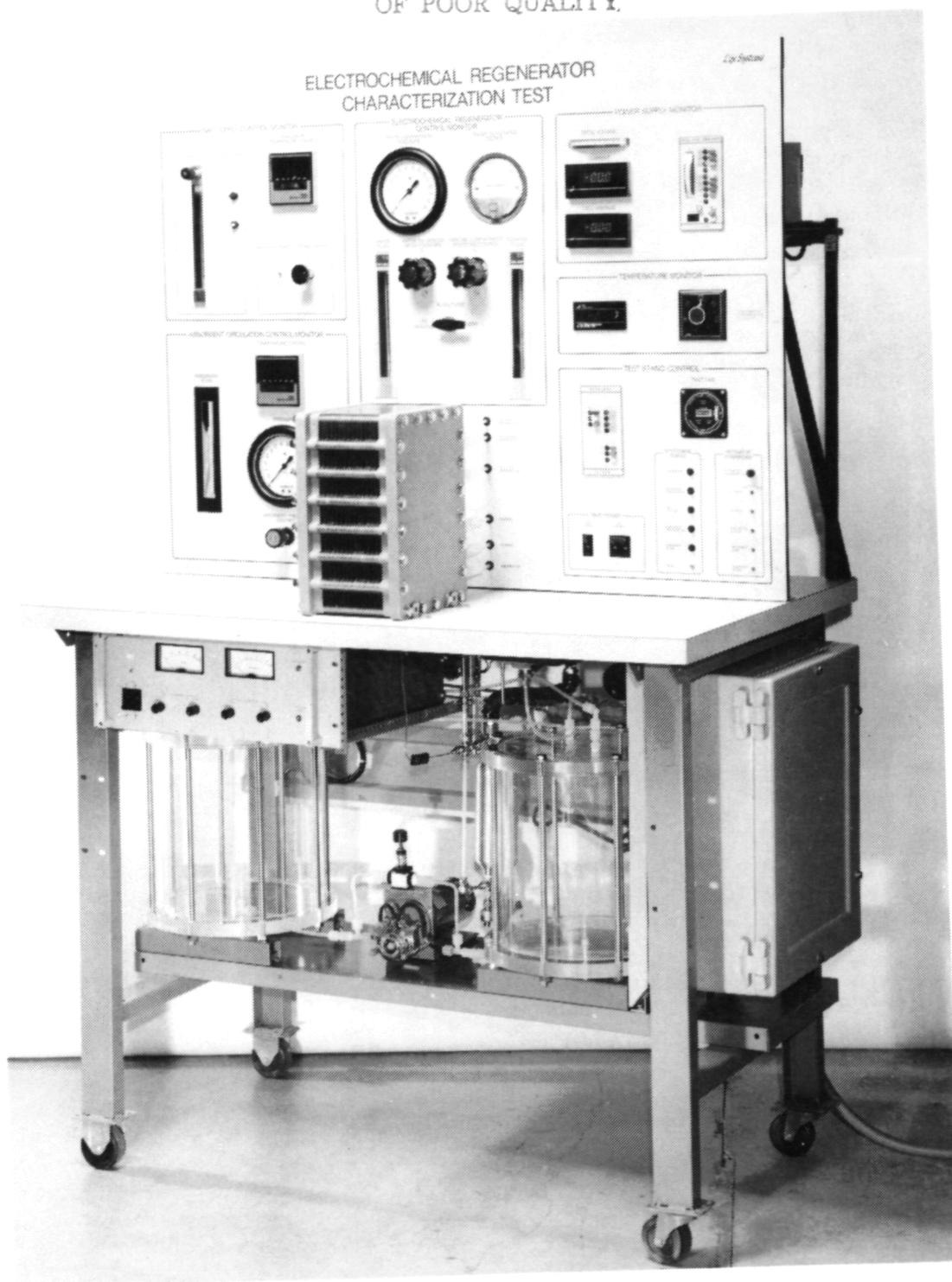


FIGURE 32 ELECTROCHEMICAL REGENERATOR TEST STAND

TABLE 8 REGENERATION RUN NO. 1 OPERATING CONDITIONS

Run Time, min	Current, A	Expend Abs. Circ. Outlet Temp., K (F)	Anode-to Cathode Delta P ^(a) kPa (psi)	Absorbent Composition, %			
				Supply		Regenerated	
				CO ₃ ⁼	OH ⁻	CO ₃ ⁼	OH ⁻
60	5	323 (121)	20 (2.9)	-	-	25.43	7.31
140	10	323 (122)	21 (3.0)	-	-	19.34	13.31
190	15	323 (122)	20 (2.9)	26.82	3.17	14.44	19.23
260	20	326 (127)	19 (2.8)	-	-	10.59	24.00
300	25	331 (136)	21 (3.1)	-	-	8.86	26.94

(a) With matrix in the feed plates.

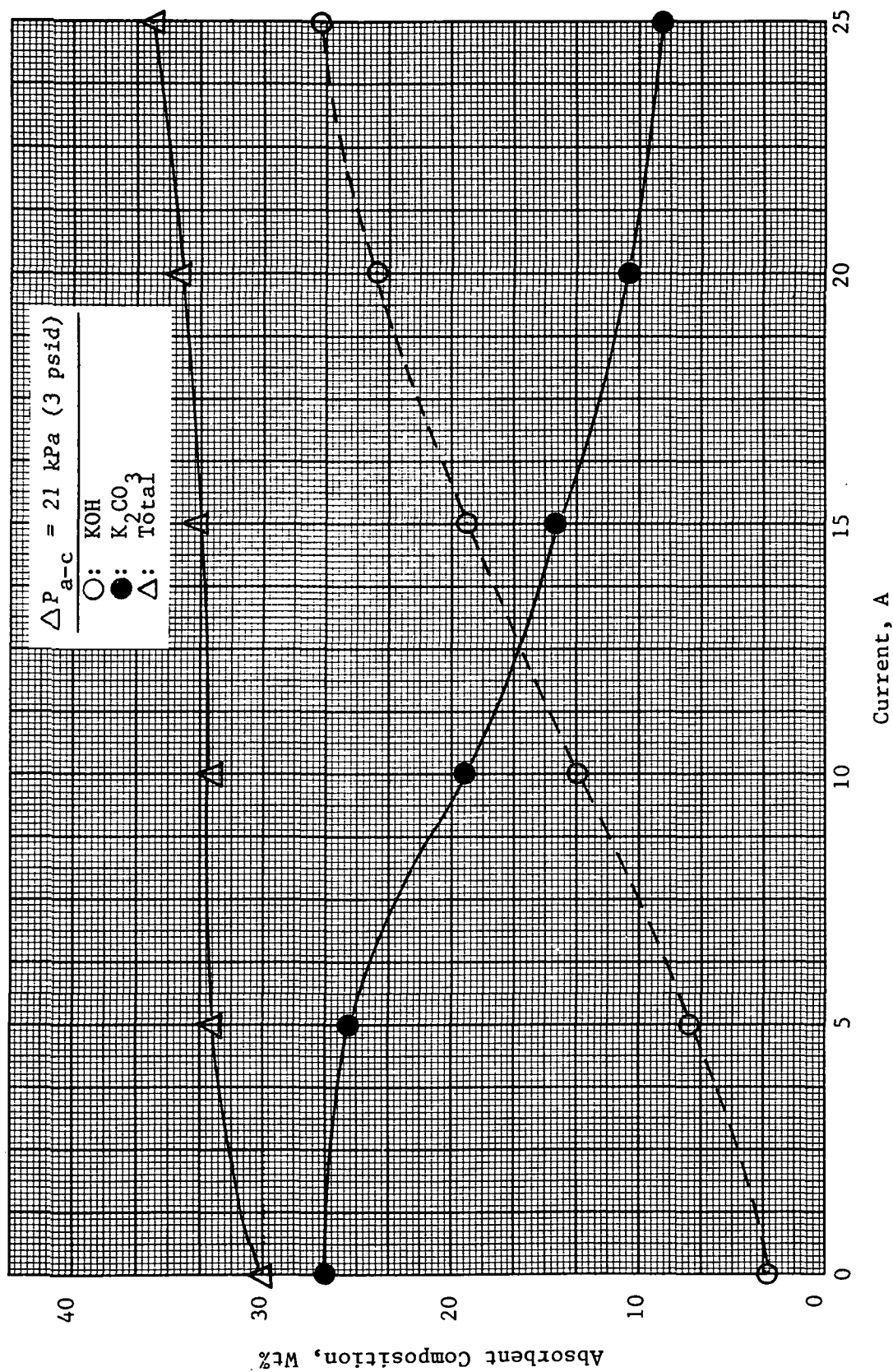


FIGURE 33 ELECTROCHEMICAL REGENERATION PERFORMANCE (RUN NO. 1)

TABLE 9 REGENERATION RUN NO. 2 OPERATING CONDITIONS

Run Time, min	Current, A	Expend Abs. Circ. Outlet Temp., K (F)	Anode-to- Cathode Delta P (a) kPa (psi)	Regenerated Absorbent Flow Rate, cc/min (in ³ /min)	Absorbent Composition, %			
					Supply	CO ₃ ⁼	HCO ₃ ⁼	Regenerated CO ₃ ⁼ OH ⁼
30	5	319 (114)	30 (4.4)	5.2 (0.32)	33.95	0.44	25.64	11.11
70	10	321 (118)	30 (4.3)	4.2 (0.26)	33.50	0.93	24.12	12.97
110	15	322 (120)	30 (4.3)	4.3 (0.26)	33.04	1.64	18.90	17.85
140	20	324 (124)	30 (4.3)	3.9 (0.24)	32.28	2.74	14.97	21.77
170	25	329 (132)	30 (4.3)	3.7 (0.23)	31.59	3.79	12.24	25.85
200	25	332 (137)	28 (4.1)	2.5 (0.15)	-	-	12.01	27.48

(a) With matrix in the feed plates.

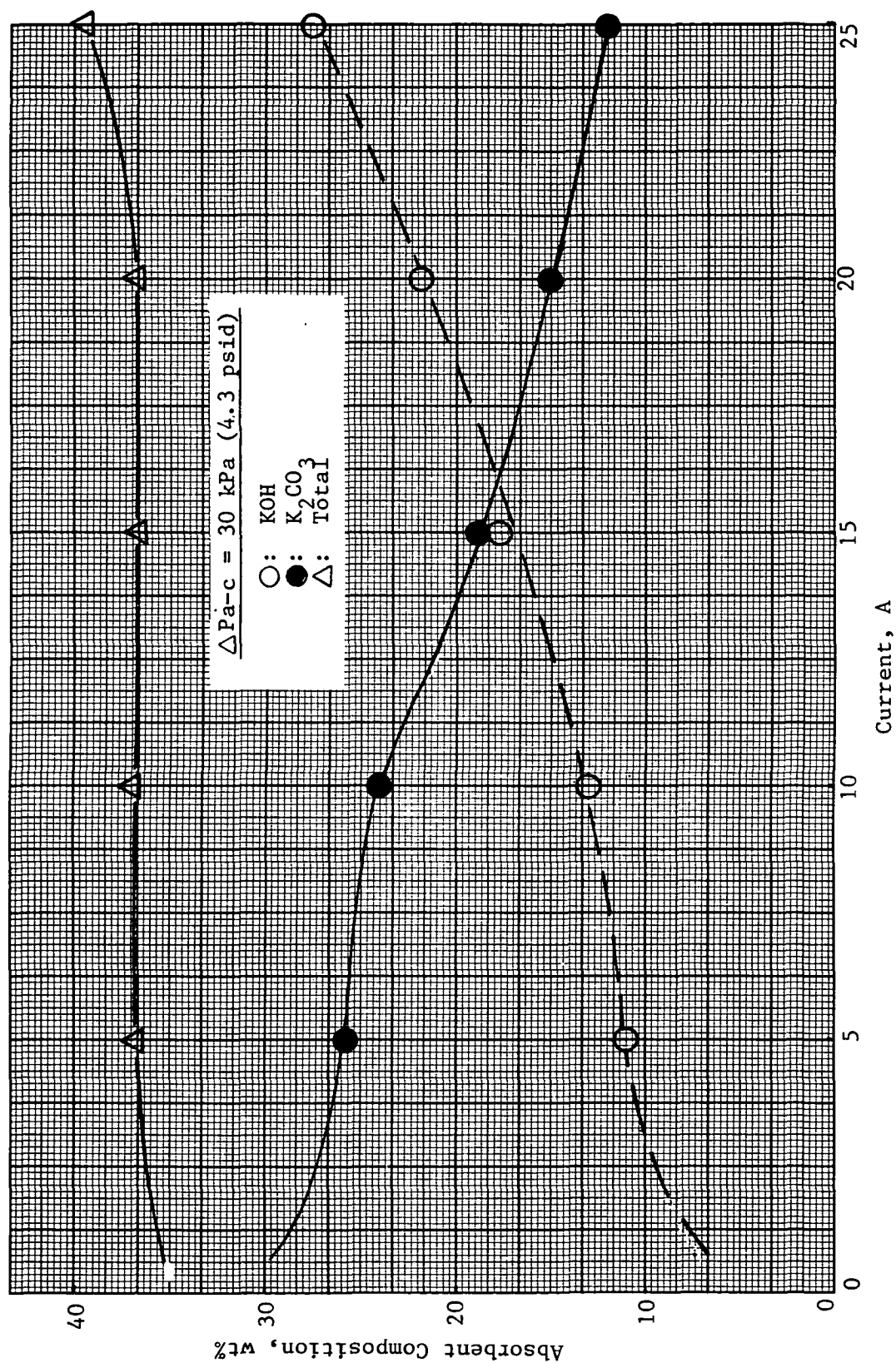


FIGURE 34 ELECTROCHEMICAL REGENERATION PERFORMANCE (RUN NO. 2)

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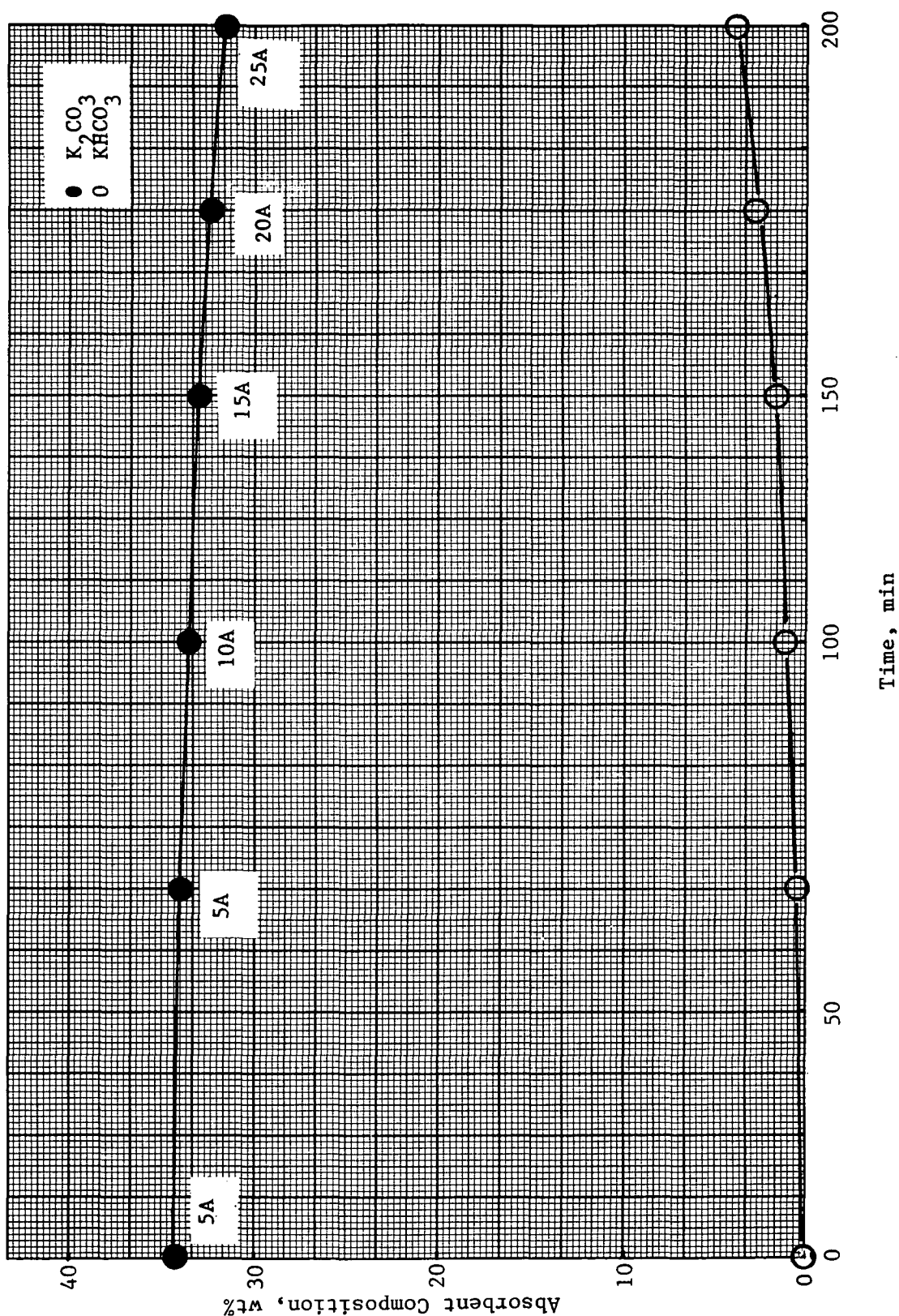


FIGURE 35 EXPENDED ABSORBENT FEED COMPOSITION CHANGE (RUN NO. 2)

The operating data for run No. 3 is shown in Table 10. All of the data was obtained at a current of 25 A. Thus, any difference in regenerated absorbent quality might be attributable to the absorbent temperature. An 262 K (11 F) absorbent temperature difference between the first and second data points produced a substantial difference in the regenerated absorbent composition. The improved quality at the higher temperature was obtained even though the absorbent supply composition was less favorable (more expended due to less OH⁻ present). The regenerated absorbent flow rates for the first two data points were very similar, eliminating this parameter as a possible explanation for the improvement in regenerated absorbent quality. The final data point, which was performed at the same temperature and current as the second data point, showed a slight improvement in the regenerated absorbent quality (again, with a more expended absorbent supply). This improvement may have been due to the lower anode-to-cathode pressure differential with the associated reduced regenerated absorbent flow. The reduced flow increases the absorbent residence time within the electrode stack which is likely to have a beneficial effect on regenerated absorbent quality.

ABSORBENT CHARACTERIZATION AND SAFETY STUDY

Absorbent Characterization

Solubility

The key properties of several candidate absorbents have been investigated. The absorbents included lithium hydroxide (LiOH), sodium hydroxide (NaOH), calcium hydroxide (Ca(OH)₂), magnesium hydroxide (Mg(OH)₂), potassium hydroxide (KOH), rubidium hydroxide (RbOH) and cesium hydroxide (CsOH). The properties of their carbonate and bicarbonate forms were also investigated.

The solubilities of Ca(OH)₂ and Mg(OH)₂ were so low they were eliminated at the beginning of the study. The solubilities of LiOH, NaOH, KOH, RbOH and CsOH are shown in Table 11.

The molarity values of the hydroxide form (-OH) of the absorbent represent their relative CO₂ absorption capacity per unit volume. That is, the larger these values are, the more CO₂ they can absorb. As to the solubility values of the carbonate and bicarbonate forms, the larger these values are, the less likely they will precipitate out in the solution as CO₂ is absorbed.

From the data available so far, it can be seen that LiOH is not desirable due to its lower solubility than either NaOH, KOH, RbOH or CsOH. The carbonate form is also undesirable because of its very low solubility. In the case of NaOH, although it has a high solubility, its carbonate salt's solubility is much lower than that of potassium, rubidium or cesium; therefore, NaOH is not desirable.

Bicarbonate solubility becomes important during the absorbent regeneration. As expended absorbent circulates through the regenerator module, it reabsorbs some of the CO₂ released at the anode. Residual hydroxide ion in the expended absorbent is converted to carbonate ion due to CO₂ reabsorption. Because of

TABLE 10. REGENERATION RUN NO. 3 OPERATING CONDITIONS

Run Time, min	Current, A	Expend. Abs. Circ. Outlet Temp., K (F)	Anode-to- Cathode Delta P ^(a) kPa (psi)	Regenerated Absorbent Flow Rate, cc/min (in ³ /min)	Absorbent Composition, %			
					Supply	Regenerated		
					CO ₃ ⁼	OH ⁻	CO ₃ ⁼	OH ⁻
6	25	314 (106)	6.9 (1.0)	12.8 (0.78)	25.29	7.83	13.76	25.06
80	25	327 (128)	6.9 (1.0)	12.9 (0.79)	28.80	4.74	11.30	26.14
120	25	327 (128)	2.8 (0.4)	11.5 (0.70)	31.87	1.30	10.33	26.02

^(a) Without matrix in the feed plates.

TABLE 11 SOLUBILITIES OF VARIOUS AQUEOUS ABSORBENTS AND THEIR
CARBONATE AND BICARBONATE FORMS AT 288.2 K (59 F)

Absorbent	MW	Solubility, wt %	Specific Gravity ^(a)	Molarity ^(a)	Molality ^(a)
LiOH	23.95	10.0 ^(b)	1.107 ^(b)	4.62	4.64
NaOH	40.0	50.0 ^(b)	1.5253 ^(b)	19.07	25.0
KOH	56.11	51.7	1.5355	14.15	19.1
RbOH	102.5	64.2	1.88	11.77	17.5
CsOH	149.9	79.4	2.77	14.75	25.7
Li ₂ CO ₃	73.89	1.36	1.014	0.19	0.19
Na ₂ CO ₃	105.99	14.1	1.1485	1.53	1.55
K ₂ CO ₃	138.2	52.2	1.5757	5.94	7.9
Rb ₂ CO ₃	230.0	81.8	2.55 ^(c)	9.07	9.4
Cs ₂ CO ₃	325.8	72.2	2.46	5.45	7.9
LiHCO ₃	69.96	5.21	1.04	0.80	0.81
NaHCO ₃	84.00	8.15	1.06	1.03	1.06
KHCO ₃	100.11	24.3	1.171 ^(b)	2.84	3.2
RbHCO ₃	146.5	35.0	1.45 ^(d)	3.46	7.9
CsHCO ₃	193.92	67.6 ^(e)	1.91 ^(e)	6.66 ^(e)	10.6

(a) At saturation.

(b) At 293.2 K (68 F).

(c) Extrapolated from available data.

(d) Estimated from the densities of RbOH and Rb₂CO₃.

(e) 70.5 wt%/1.9/7.16 M at 308 K (95 F).

the high CO_2 concentration in the anode compartment (potentially 50 percent) further reaction of the carbonate to bicarbonate will occur. In fact, this will occur to an extent such that equilibrium is reached between the carbonate, bicarbonate and CO_2 at the temperature and pressure conditions of the regenerator module. It is important that the bicarbonate solubility be well above the equilibrium bicarbonate concentration to avoid bicarbonate precipitation in the expended absorbent. It is seen in Table 11 that the CsHCO_3 solubility (expressed as molarity) is much greater than that of KHCO_3 or RbHCO_3 .

Carbon Dioxide and Moisture Absorption Capacity Comparison

Using the data in Table 11, CO_2 absorption capacities of the three absorbents, i.e., KOH, RbOH and CsOH, at various percentages of their saturation concentrations have been determined and shown in Table 12. Complete conversion of the hydroxide forms of the absorbent to their carbonate forms was used as the basis for comparison. As can be seen in Table 12 CsOH has the highest CO_2 absorption capacity per unit volume among all absorbents at near their bicarbonate salts' saturation concentrations.

As for the moisture absorption capability of the absorbents, literature search did not produce much information on water vapor pressure data of RbOH and CsOH. Attempts have been made to apply the Raoult's law for the development correlation between the water vapor pressure and the concentration of the absorbents. When the validity of the application of this law was checked by comparing the actual water vapor pressure data of aqueous KOH solutions and the values calculated by using the Raoult's formula, there were large discrepancies at high concentrations, which are of our interest. This is most probably due to the dissociation of the solute molecules and the loss of free water molecules to the hydration of the dissociated ions.

An experimental test setup was prepared to measure the water vapor pressure of RbOH and CsOH and their corresponding carbonates and mixtures. This technique utilized a General Eastern dew point sensor mounted in an Erlenmeyer flask. This apparatus was located in a temperature controlled chamber (see Figure 36). The water vapor pressure of the solution is given by the dew point temperature.

The validity of this technique was established by comparing experimental measurements of a 25 wt% KOH solution to literature values. The results of this analysis listed this report should be accurate to 3.5% over the temperature range tested.

The experimental procedure consisted of first adding approximately 70 cm^3 (4.3 in^3) of sample (known composition) to the 500 cm^3 (30 in^3) flask. Next, the sensor was sealed in the flask using a foam gasket material. This apparatus was placed in the temperature controlled chamber. Dew point measurements were recorded at the desired temperature until a steady state was achieved. This state was determined by the condition of a rate of change in the dew point measurement of less than 0.01 K/min (0.02 F/min). Typically, this step would take about 45 to 60 minutes for temperature stabilization. This step was then repeated at several other temperatures in the range from 294 to 317 K (70 to 130 F).

TABLE 12 CO₂ ABSORPTION CAPCITIES OF ABSORBENTS

Absorbents	% of Saturation	Concentration		Density	CO ₂ Absorption Capacity	
		Normality	Wt, %		kg/dm ³	(lb CO ₂ /l)
KOH	20	2.83	14.1	1.126	0.062	(0.137)
	30	4.25	20.2	1.183	0.094	(0.207)
	40	5.66	25.7	1.237	0.125	(0.275)
	50	7.08	30.8	1.289	0.156	(0.343)
	60	8.49	35.6	1.339	0.187	(0.412)
RbOH	20	2.35	14.1	1.217	0.052	(0.115)
	30	3.53	20.2	1.355	0.078	(0.171)
	40	4.71	25.7	1.509	0.104	(0.228)
	50	5.89	40.0	1.510	0.130	(0.285)
	60	7.06	45.4	1.585	0.156	(0.343)
CsOH	30	4.43	42.0	1.630	0.097	(0.213)
	40	5.90	50.1	1.762	0.130	(0.286)
	50	7.38	55.8	1.938	0.163	(0.358)
	60	8.85	63.3	2.120	0.195	(0.429)

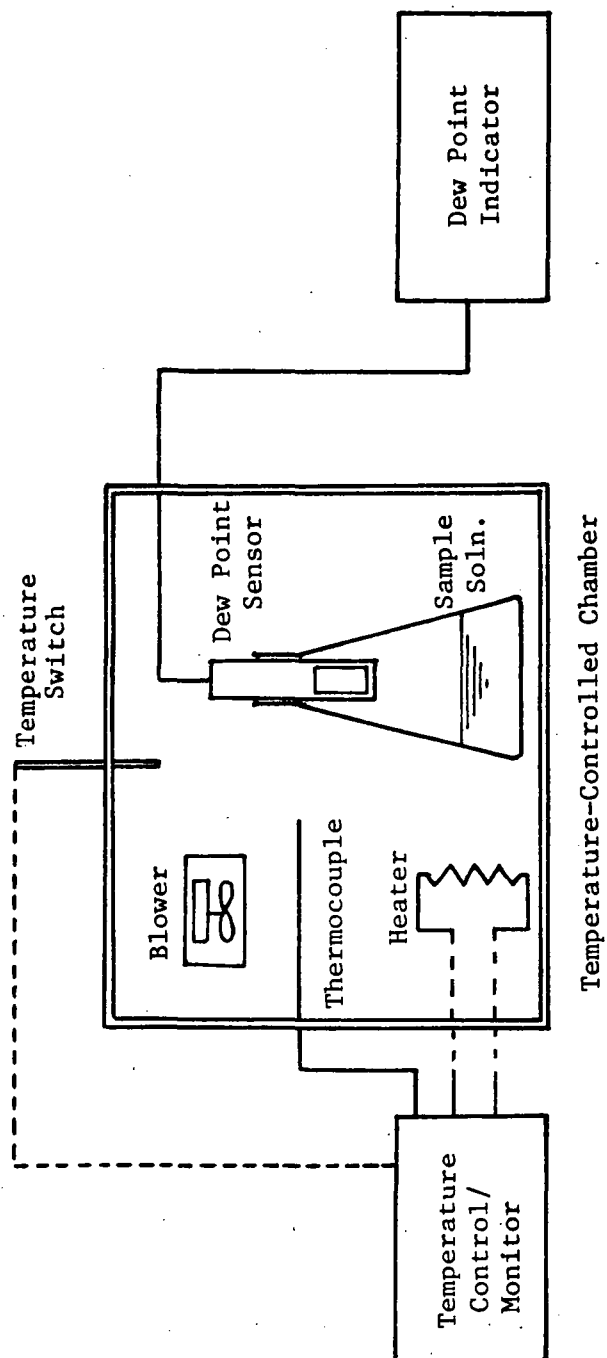


FIGURE 36 WATER VAPOR PRESSURE MEASUREMENT SETUP

The results of the measurements are shown in Figures 37 and 38 for the hydroxide and carbonate forms of the absorbents, respectively. As can be seen in the figures, the cesium and rubidium absorbents exhibit lower water vapor pressure than the potassium absorbent in either hydroxide or carbonate form. This means that the moisture absorption driving forces are higher with the cesium and rubidium absorbent than the potassium absorbent.

Heat of Reaction Comparison

The heat of reactions of the three absorbents, KOH, RbOH and CsOH, have been calculated using the heats of formation of the chemicals involved. The reaction equation: $2 \text{ MOH(aq)} + \text{CO}_2(\text{g}) \longrightarrow \text{M}_2\text{CO}_3(\text{aq}) + \text{H}_2\text{O(l)}$, where M stands for potassium, rubidium or cesium, was used as the basis.

The heats of reactions for aqueous KOH, RbOH and CsOH solutions absorbing 0.45 kg (1.0 lb) of CO_2 are 303, 304 and 243 Whr (-1033, -1036 and -829 Btu), respectively, indicating that the cesium absorbent generates the least amount of heat.

The heat generated by the absorption of 0.57 kg (1.25 lb) of metabolic moisture is 385 Whr (1,313 Btu), regardless of absorbents.

pH of Absorbents

pH measurements also were made for the potassium, rubidium and cesium absorbents of 100% hydroxide form, mixture of 67% hydroxide form and 33% carbonate form, mixture of 33% hydroxide form and 67% carbonate form and 100% carbonate form, at the total concentration level of 7.0 N. The MCI Automatic Titrator Model GT-05, which is equipped with a pH electrode, was used for the measurements. The results are shown in Table 13 for the potassium, rubidium and cesium compounds. As can be seen in Table 13, the difference in pH values between the 100% OH form and the 100% CO_3 form is the largest with rubidium (3.16) followed by potassium (2.58) and cesium (2.42).

Conductivity of Absorbents

Conductivity measurements of the absorbents of various compositions were taken with a conductivity bridge and a pipette style conductivity cell with a volume of 3 cm³ (0.2 in³) and a cell constant, K, equal to 50. Room temperature measurements were made at 297 K (75 F). Elevated temperature data was collected with the conductivity cell and subject solutions thermally equilibrated inside an oven set at 308 K (95 F). Prior to each measurement, the conductivity cell was rinsed with distilled water and two 3 cm³ (0.2 in³) aliquots of the solution to be tested.

Specific conductivities of the absorbents at various compositions are shown in Figures 39 and 40 for 297 K (75 F) and 308 K (95 F), respectively.

Absorbent Comparison and Recommendation

Based on the data obtained through the measurements of densities, solubilities, water vapor pressures and pH and specific conductivity values and calculations of the CO_2 absorption capacities and heat of reactions, a comparison table was

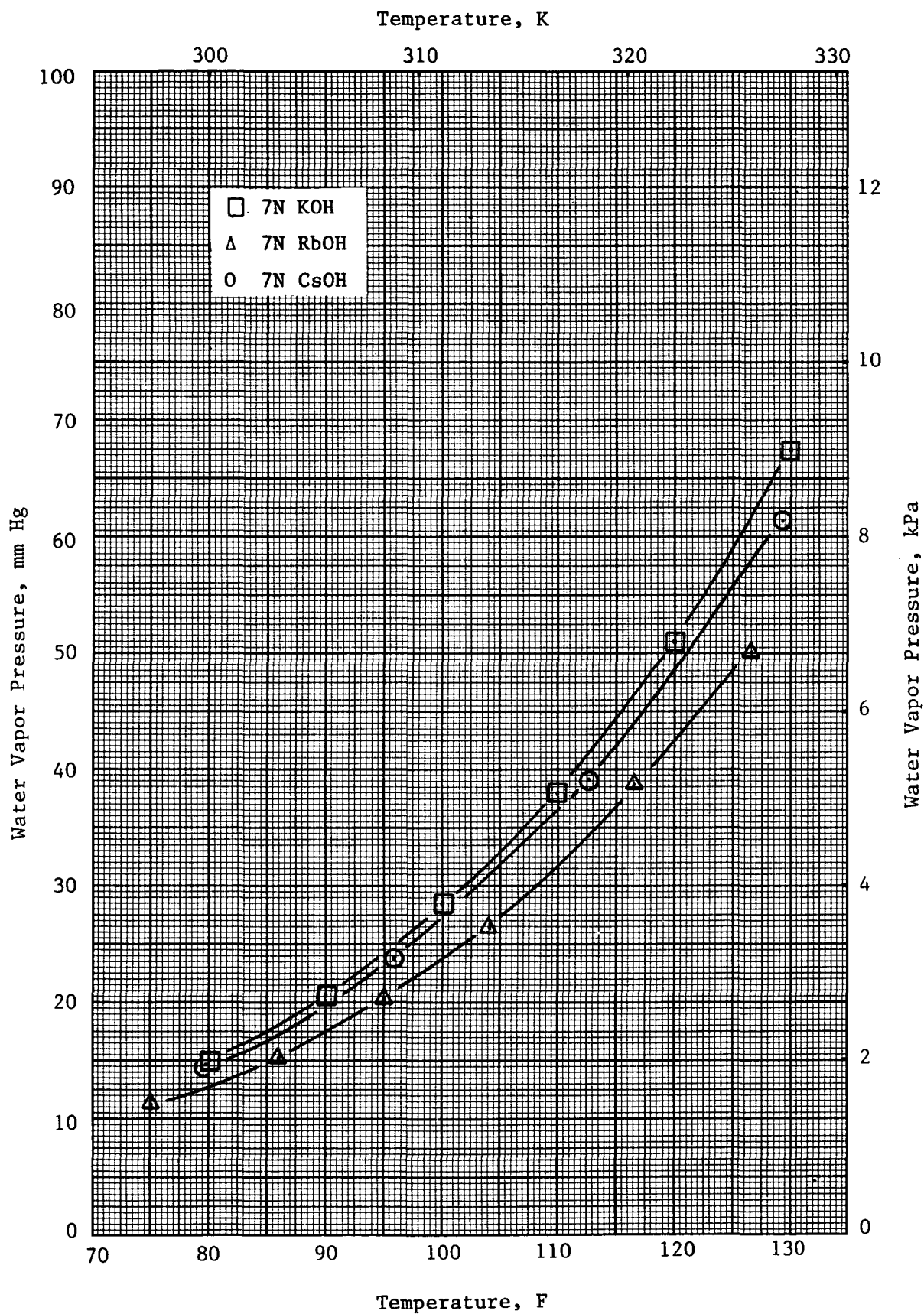


FIGURE 37 WATER VAPOR PRESSURE OF AQUEOUS KOH, RbOH AND CsOH SOLUTIONS

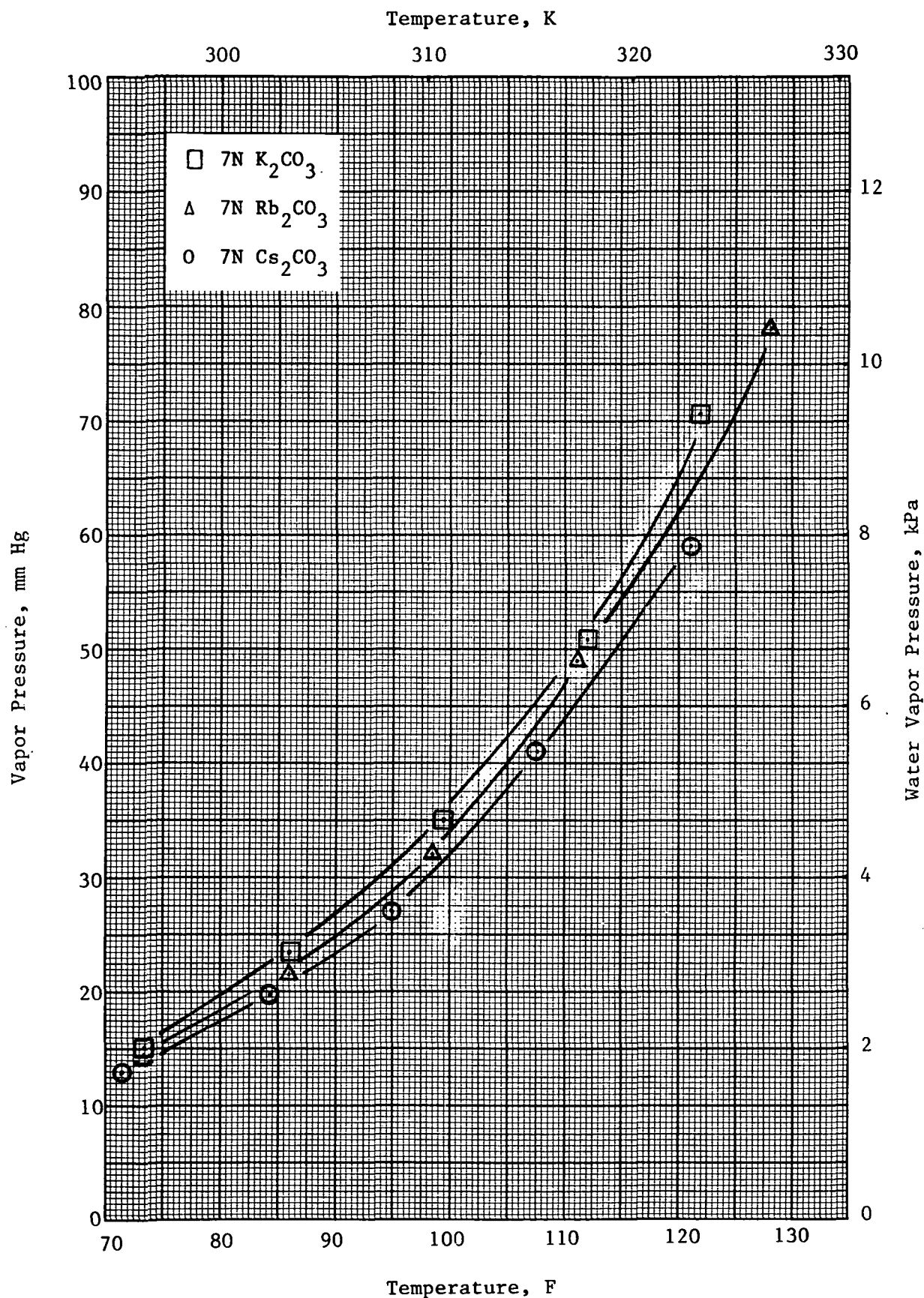


FIGURE 38 WATER VAPOR PRESSURE OF AQUEOUS K_2CO_3 , Rb_2CO_3 AND Cs_2CO_3 SOLUTIONS

TABLE 13 pH OF POTASSIUM, RUBIDIUM AND CESIUM ABSORBENTS IN HYDROXIDE, CARBONATE AND MIXTURE STATES

Nominal Concentration, N	Cations					
	Actual Concentration, N			pH ^(a)		
	K	Rb	Cs	K	Rb	Cs
7.00 OH ⁻	7.01	7.00	7.00	15.54	15.71	15.43
4.67 OH ⁻	4.67	4.67	4.67	15.33	15.54	15.28
2.33 CO ₃ ⁼	2.46	2.33	2.33			
2.33 OH ⁻	2.40	2.33	2.34	15.10	15.26	15.09
4.67 CO ₃ ⁼	4.67	4.67	4.67			
7.00 CO ₃ ⁼	7.00	7.00	7.00	12.96	12.55	13.01

(a) Measured at 296 K (73 F).

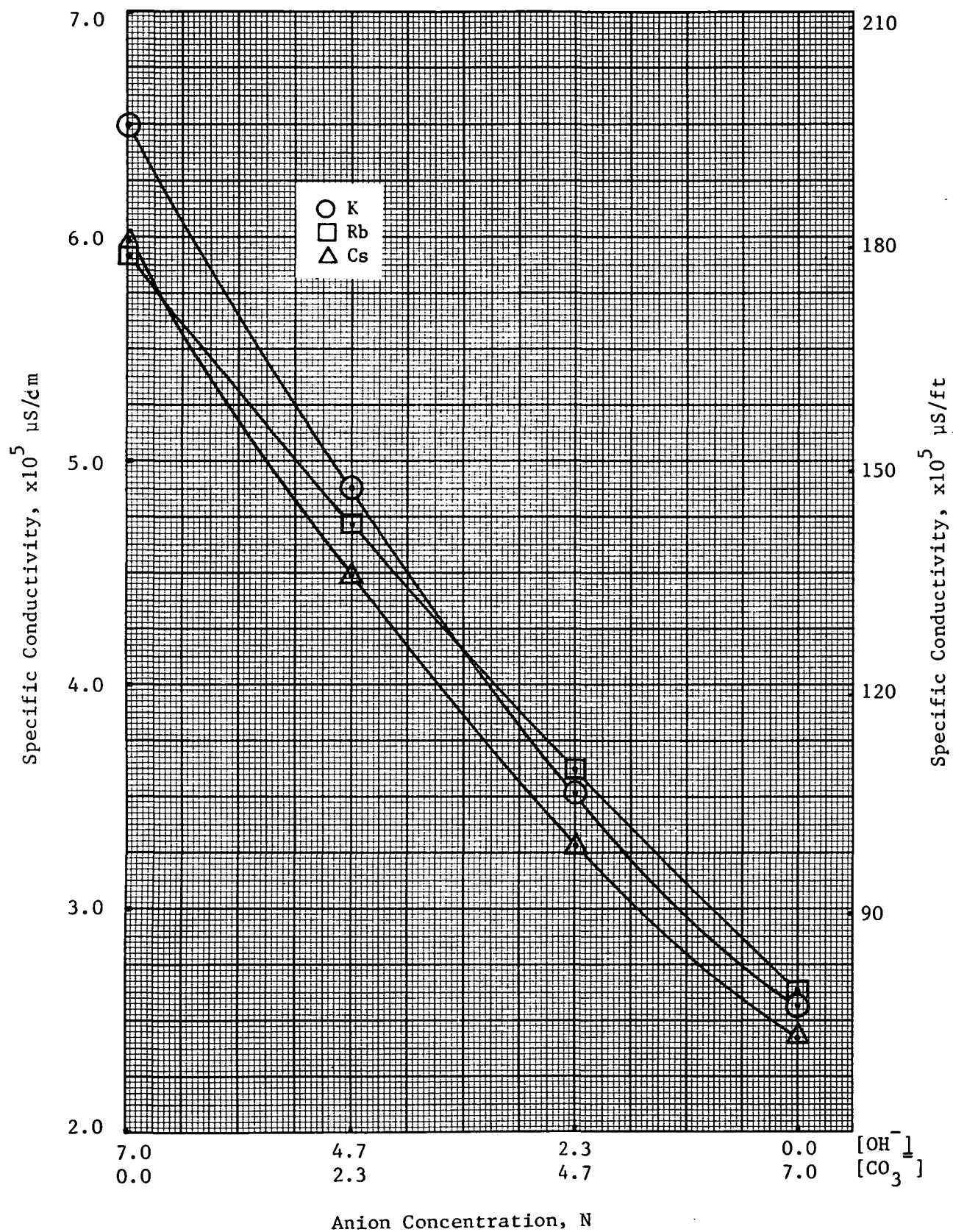


FIGURE 39 ABSORBENT CONDUCTIVITY VERSUS ANION COMPOSITION
AT 297 K (75 F)

Anion Concentration	Specific Conductivity, $\times 10^5 \mu\text{S/cm} (\mu\text{S/ft})$		
	K	Rb	Cs
7.00 N OH^-	6.49 (198)	5.91 (180)	5.98 (182)
4.67 N OH^-	4.88 (149)	4.72 (144)	4.49 (137)
2.33 N $\text{CO}_3^{=}$			
2.33 N OH^-	3.51 (107)	3.62 (110)	3.28 (100)
4.67 N $\text{CO}_3^{=}$			
7.00 N $\text{CO}_3^{=}$	2.57 (78)	2.63 (80)	2.42 (74)

Figure 39 - continued

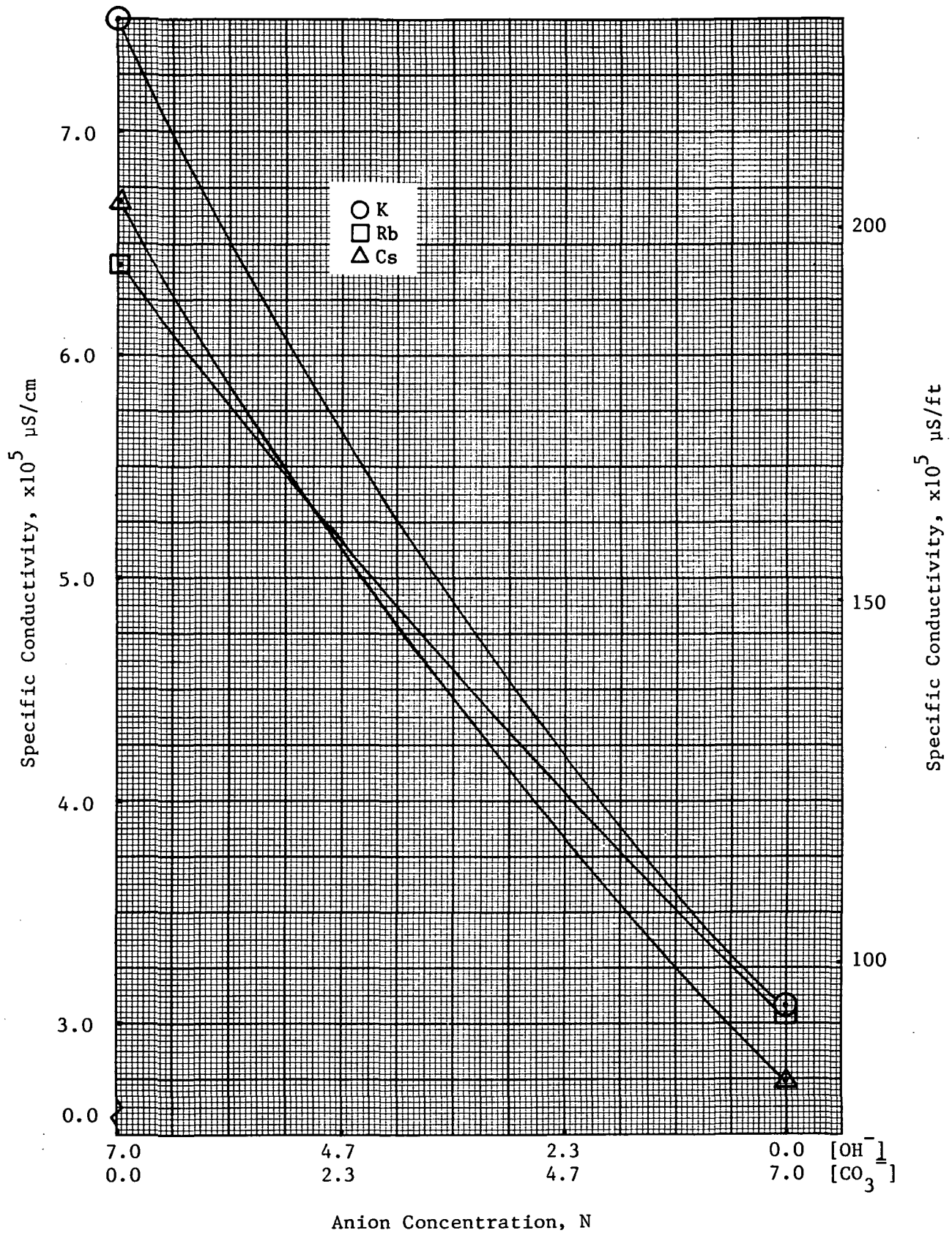


FIGURE 40 ABSORBENT CONDUCTIVITY VERSUS ANION COMPOSITION
AT 308 K (95 F)

Anion Concentration	Specific Conductivity, $\times 10^5 \mu\text{S/cm}$ ($\mu\text{S/ft}$)		
	K	Rb	Cs
7.00 N OH ⁻	7.50 (229)	6.40 (195)	6.69 (204)
7.00 N CO ₃ ⁼	3.07 (94)	3.05 (93)	2.75 (84)

Figure 40 - continued

prepared and is shown in Table 14. The ratings of the absorbent in each category are shown and their summations are given. In rating the absorbent for each category, 1 is given to the best absorbent. Where there is hardly any difference, the same numbers are given. As can be seen in the comparison, CsOH is the best absorbent overall and is recommended as the absorbent to be used in the future.

Safety Design

Absorbent Safety

Although careful design can eliminate the possibility of danger to an EVA crew from the exposure to the alkaline absorbents (liquid, solid, weakly or strongly basic) used in removal of metabolic CO₂ and water, safety provisions are required to protect crewmen from the undesirable effects of the absorbents. In this section, we discuss and present the safety considerations which have been incorporated and also those that can be included in the following prototype hardware development.

Safety consideration in the three different aspects, i.e., material selection, absorbent bed fabrication, and the Absorber Module design, will be discussed. The safety design features of the Absorber Module are shown in Figure 41.

Material Selection for the Absorbent Bed

Membrane

In the fabrication of the absorbent bed, microporous hydrophobic membrane of desirable mechanical strength is used in providing space where aqueous alkaline absorbent is retained and circulated. Although the membranes have pores open to vent gas, they provide resistance to the breakthrough of the absorbent into the vent gas space due to the membranes' hydrophobicity. The magnitude of the breakthrough pressure depends on the maximum pore size of the membrane.

The membranes that have been used in the fabrication of the pressure absorbent bed have the pore size that provides 140 kPa (20 psid) of minimum water breakthrough pressure. This pressure is far greater than what can develop in actual operation. In fact, with an accumulator installed which will take care of any absorbent volume increase resulting from 5 hours of metabolic CO₂ and moisture absorption, there will hardly be any differential pressure developing between the absorbent and the vent gas spaces.

The membranes of even smaller pore sizes can be used if larger breakthrough pressures are desired. However, as the water breakthrough pressure of the membranes increases, the resistance of the membranes to the diffusion of gases increases also.

Bonding Material

In order to provide spaces where aqueous absorbent is retained and separated from the vent gas, the hydrophobic membranes have to be bonded at various places. The bonding material also comes in contact with the alkaline

TABLE 14 ABSORBENT COMPARISON^(a)

	<u>K</u>	<u>Rb</u>	<u>Cs</u>
Capacity			
• CO ₂	3	2	1
• Moisture	2	1	1
Solubility			
• OH ⁻	2	3	1
• CO ₃ ⁼	2	1	2
• HCO ₃ ⁻	3	2	1
Heat of Reaction			
• OH ⁻ → CO ₃ ⁼	2	2	1
Conversion			
Determinability	<u>1</u>	<u>1</u>	<u>1</u>
	15	12	8

(a) 1: best, 3: worst.

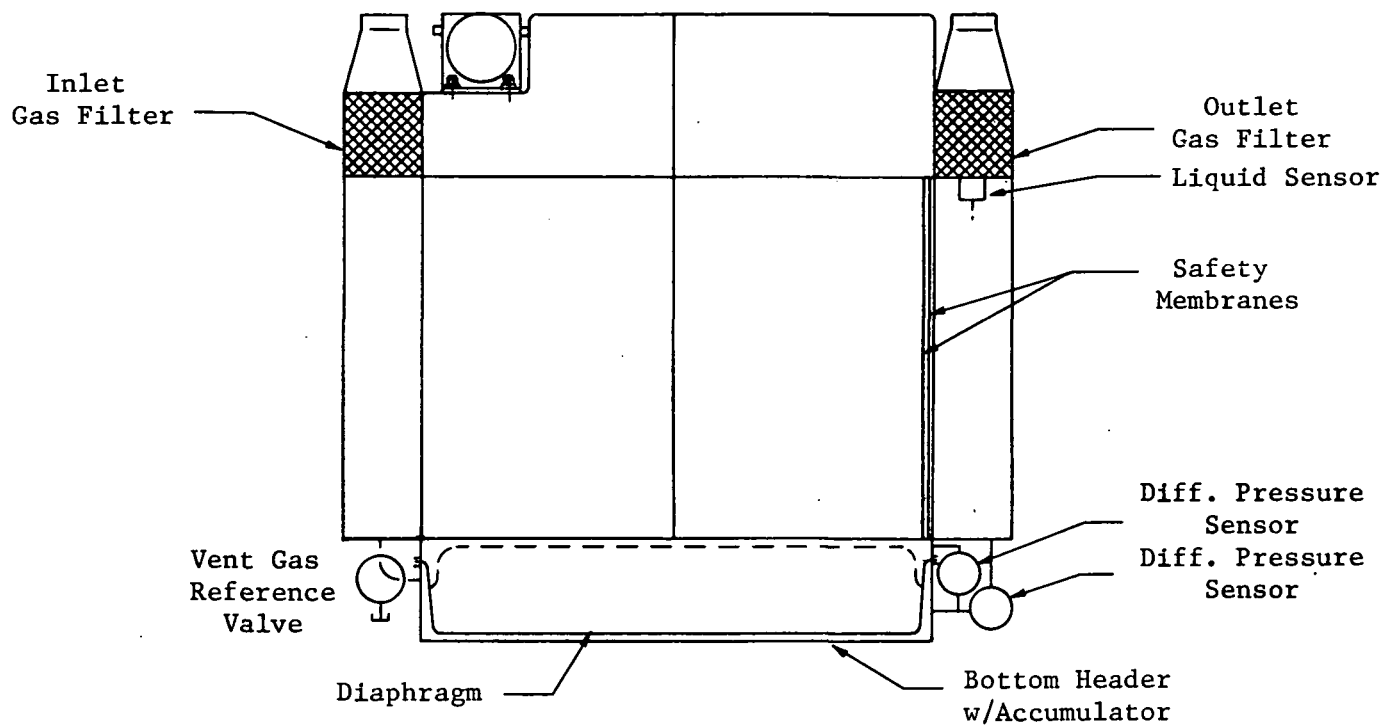


FIGURE 41 ABSORBER MODULE SAFETY DESIGN

absorbent. The temperature of the absorbent can also vary during EVA operation due to the exothermic nature of the CO_2 and moisture absorption reactions. Therefore, the bonding material to be used has to be both chemically and thermally stable.

Fabrication

Membrane Core

A membrane core is made of a membrane sealed around its outer edge. Each membrane core is pressure tested in a specially prepared differential pressure test fixture for the detection of any pinhole leaks or water breakthrough. This step eliminates the possibility of any defective membrane being used in the fabrication of an absorbent bed.

Bonding

Chemically and thermally stable bonding agent has been used in the fabrication of the current absorbent bed. Although it is time-consuming and difficult to fabricate an absorbent bed by bonding individual membrane cores, this method is the only one developed so far that can produce a reliable absorbent bed.

Design

Accumulator

During the absorption of metabolic CO_2 and moisture, the volume of the absorbent increases with time. At the nominal conditions, the volume increase during the five hours of EVA will amount to approximately 790 cm^3 (48 in^3). Unless an accumulator that can accommodate this volume increase is installed, the membranes of the absorbent bed will experience excessive pressure which may cause either the breakthrough of the absorbent, the rupture of the membranes or the breakage of the bonding.

An accumulator of the aforementioned capacity with the opposite side of the absorbent referenced to the vent gas will eliminate any possibility of excessive differential pressure buildup during normal operation.

A differential pressure sensor between the absorbent and the vent gas spaces can be installed as a positive measure of detecting any buildup of differential pressure.

Safety Membranes

In order to protect a crewman in case of an absorbent leak, two safety membranes supported by a screen can be installed as a barrier at the vent gas outlet of the absorbent bed. The membranes and the support screen can be bonded to the outlet frame without increasing the volume of the bed or the absorber module.

The requirements of the safety membranes are:

1. Minimum vent gas flow pressure drop
2. Hydrophobic

The membrane should have large porosity and pore size for low vent gas flow pressure drop. It also should be hydrophobic so that no liquid can be easily pushed through the membrane by the pressure from the vent gas flow. Listed in Table 15 are four commercially available membranes that can be used for this purpose.

A pressure sensor for the differential pressure between the vent gas inlet and outlet can be used as a safety device to detect any differential pressure increase due to blockage of the safety membrane pores by any leaked absorbent.

Liquid Sensor

A liquid sensor for the detection of any leaked absorbent can be installed at the vent gas outlet gas filter to warn the crewman in EVA of the leakage. This sensor is located downstream of the safety membrane. To insure that absorbent leakage does not get into the vent gas loop, another hydrophobic membrane will be utilized in the outlet vent gas filter. Thus, if absorbent leakage from the safety membrane is not immediately detected by the liquid sensor, it will still be unable to enter the vent gas loop due to the added protection provided by the membrane.

Gas Filters

Gas filters consisting of active carbon pellets and particulate filters can be installed at both vent gas inlet and outlet. The gas filter at the inlet will remove any particulate and trace contaminants in the incoming vent gas. As discussed above, the outlet gas filter will utilize a low pressure drop, hydrophobic filter which provides both particulate removal and liquid retention. A trace contaminant bed will also be used.

Sizing of the carbon beds for the ERCA absorber bed particulate/trace contaminant filters, GF1 and GF2 has been performed. The contaminants considered in the sizing, along with their generation rates, are given in Table 16. Also included in the table are the Space Maximum Allowable Concentrations (SMAC) and the time required to reach SMAC. It is seen that only two contaminants, ammonia and methyl mercaptan, reach the SMAC limit within a five-hour EVA. As such, these two contaminants were the primary drivers in the carbon bed sizing.

Due to activated carbon's very low capacity for ammonia, its removal by physical adsorption would require an excessively large carbon bed. The physical adsorption of methyl mercaptan is also difficult. For this reason, it is necessary to use impregnated carbons with improved capacity. These impregnated carbons, however, are non-regenerable, necessitating that the carbon beds (actually the complete particulate/trace contaminant filter assemblies) be periodically replaced.

TABLE 15 SAFETY MEMBRANE PROPERTIES

Item No.	Thickness, mm (Mil)	Water Breakthrough Pressure, cm H ₂ O (in H ₂ O)	Air Flow ^(a) Delta P, cm H ₂ O (in H ₂ O)
1	0.48 (19)	21.0 (8.3)	3.3 (1.3)
2	0.64 (25)	28.2 (11.1)	3.8 (1.5)
3	0.13~0.38 (5~15)	35.3 (13.9)	3.0 (1.2) ^(b)
4	0.13~0.38 (5~15)	17.5 (6.9)	1.0 (0.4) ^(b)

(a) Based on 170 dm³/min (6 cfm) at normal temperature and pressure.

(b) Average values.

TABLE 16 VENT GAS TRACE CONTAMINANT LOAD

Contaminant	Generation Rate,		SMAC, ^(a)	Time to Reach SMAC, ^(b) hr
	g mole/man-day (lb mole/man-day)	mg/hr (lb/hr)	mg/m ³ (lb/ft ³)	
Ammonia	1.47 x 10 ⁻² (3.24 x 10 ⁻⁵)	10.41 (2.29 x 10 ⁻⁵)	17.4 (1.35 x 10 ⁻³)	0.05
Methane	2.94 x 10 ⁻³ (6.48 x 10 ⁻⁶)	1.96 (4.32 x 10 ⁻⁶)	1771 (1.38 x 10 ⁻¹)	25.5
Acetaldehyde	1.88 x 10 ⁻⁶ (4.14 x 10 ⁻⁹)	0.00345 (7.61 x 10 ⁻⁹)	54.0 (4.20 x 10 ⁻³)	443
Acetone	2.24 x 10 ⁻⁶ (4.94 x 10 ⁻⁹)	0.00541 (1.19 x 10 ⁻⁸)	712.5 (5.55 x 10 ⁻²)	3727
Ethanol	8.68 x 10 ⁻⁵ (1.91 x 10 ⁻⁷)	0.166 (3.66 x 10 ⁻⁷)	94.0 (7.32 x 10 ⁻³)	16.1
Methanol	4.37 x 10 ⁻⁵ (9.63 x 10 ⁻⁸)	0.0583 (1.29 x 10 ⁻⁷)	52.4 (4.08 x 10 ⁻³)	25.5
N-butanol	1.75 x 10 ⁻⁵ (3.86 x 10 ⁻⁸)	0.0540 (1.19 x 10 ⁻⁷)	121.0 (9.42 x 10 ⁻³)	63.5
Methyl Mercaptan	1.73 x 10 ⁻⁵ (3.81 x 10 ⁻⁸)	0.0346 (7.63 x 10 ⁻⁸)	0.20 (1.56 x 10 ⁻⁵)	0.16
Hydrogen Sulfide	2.20 x 10 ⁻⁶ (4.85 x 10 ⁻⁹)	0.00317 (6.99 x 10 ⁻⁹)	2.80 (2.18 x 10 ⁻⁴)	25.0

(a) Space maximum allowable concentration. Reference NHB 8060.1, Appendix D.

(b) Based on vent gas space of 57 dm³ (2.0 ft³) and initial concentration equal to 0.50 x (SMAC).

Ammonia removal is accomplished by using a phosphoric acid-impregnated carbon. With the high capacity of this impregnated carbon for ammonia, only 1.0 g (0.0022 lb) of carbon is required for a five-hour EVA. With the projected volume available for the particulate/trace contaminant filter, 120 cm³ (7.3 in³), enough carbon can be provided to remove ammonia for 58 EVA's. In addition to the ammonia removal capability, the impregnated carbon retains the ability to physically adsorb organic contaminants. The removal of the organic contaminants (excluding methyl mercaptan), however, is not required because none of them reach the SMAC level within the five-hour EVA.

Methyl mercaptan does reach its SMAC level within a short time and, therefore, must be removed. Again, removal by physical adsorption would result in a fairly large bed. The absorption can be greatly improved through the use of a sodium hydroxide-impregnated carbon. This carbon would also provide hydrogen sulfide removal. Because of the very low generation rates of both methyl mercaptan and hydrogen sulfide, their removal over the 58 EVA periods requires less than 1.0 g (0.0022 lb) of the impregnated carbon.

The inlet filter, GF1, will thus be composed of a carbon bed with phosphoric acid-impregnated carbon for ammonia removal and a small amount of sodium hydroxide-impregnated carbon for methyl mercaptan and hydrogen sulfide removal. The carbon will also be capable of providing peak organic and odor control. A particulate filter located upstream of the carbon bed and dust retention filter downstream of the carbon bed complete the GF1 assembly. The outlet filter, GF2, consists of a hydrophobic membrane for liquid and particulate retention. A phosphoric acid-impregnated carbon bed downstream of the membrane provides secondary trace contaminant control and also serves to neutralize any absorbent, in the unlikely event of a failure of the hydrophobic membrane (note that the hydrophobic membrane in GF2 is itself a third level of protection against absorbent entering the vent gas loop. The impregnated carbon thus acts as a fourth level of protection). A dust retention filter downstream of the carbon bed completes the GF2 assembly.

HUMIDITY CONTROL

The humidity control requirement of extravehicular activities has been determined from the nominal vent gas inlet and outlet conditions, i.e., 296 K (72 F) and 282 K (48 F) for the inlet and outlet vent gas dew point temperatures. These dew points correspond to the moisture partial pressure of 2.67 (20.06) and 1.14 kPa (8.54 mm Hg), respectively. At the vent gas flow rate of 170 dm³/min (6 acfm) at 297 K (75 F), the moisture removal rate is calculated as shown below:

$$\dot{m}_{H_2O} = \frac{M_{H_2O}}{RT} [(p_{H_2O})_{in} - (p_{H_2O})_{out}] \dot{V}$$

where:

\dot{m}_{H_2O} = moisture removal rate, g/min (lb/min)

M_{H_2O} = molecular weight of H₂O, 18.0

$(p_{H_2O})_{in}$ = moisture partial pressure of vent gas at inlet, 0.0273 kg/cm^2
(20.06 mm Hg)

$(p_{H_2O})_{out}$ = moisture partial pressure of vent gas at outlet, 0.0116 kg/cm^2
(8.54 mm Hg)

R = gas constant, $0.08478 \text{ (kg/cm}^2) \cdot \text{dm}^3/\text{gmole} \cdot \text{K}$
(555 mm Hg-ft³/lb mole · R)

T = vent gas temperature, 297 K (535 R)

\dot{V} = vent gas flow rate, $28.3 \text{ dm}^3/\text{min}$ (cfm)

Therefore,

$$\begin{aligned} \dot{m}_{H_2O} &= \frac{18 \times (20.06 - 8.54) \times 6}{555 \times 535} \quad \text{or} \quad \frac{18 \times (0.0273 - 0.0116) \times 6 \times 28.3}{0.08478 \times 297} \\ &= 0.004195 \text{ lb/min} \quad = 1.906 \text{ g/min} \\ &= 0.252 \text{ lb/hr} \quad = 0.114 \text{ kg/hr} \end{aligned}$$

Cooling Requirement

The temperature rise of the absorber module due to the absorption of CO_2 and moisture at various metabolic rate has been analyzed. A simplified thermal balance diagram is shown in Figure 42. Carbon dioxide and moisture absorption rates of 0.091 (0.20) and 0.114 kg/hr (0.25 lb/hr) at the nominal metabolic rate of 293 W (1,000 Btu/hr) were used. These were assumed to change proportionally to the metabolic rate. The cooling water rate of 13.6 kg/hr (30 lb/hr or 0.06 gpm) was used.

The thermal balance can be written as:

$$\begin{aligned} \text{Heat Generation} &= \text{Heat Accumulation in the Absorber} + \\ &\quad \text{Heat Carried Out by Vent Gas} + \\ &\quad \text{Heat Carried Out by Cooling Water} \end{aligned}$$

Using the symbols shown in Figure 42, the above can be written as:

$$\frac{dH}{dt} = MC_p \frac{dT}{dt} + \dot{m}C_p (T_o - T_i) + \dot{m}_c C_p (T_{co} - T_{ci})$$

The heat generation term, dH/dt , is:

$$\begin{aligned} \frac{dH}{dt} &= [(0.20 \text{ lb } \text{CO}_2/\text{hr}) (829 \text{ Btu/lb } \text{CO}_2) + (0.25 \text{ lb } \text{H}_2\text{O}/\text{hr}) \times \\ &\quad (1,050 \text{ Btu/lb } \text{H}_2\text{O})] \times (G/1,000) \\ &= 0.429G \text{ Btu/hr or } 0.126G \text{ W} \end{aligned}$$

where G is the metabolic rate and 534 Whr/kg (829 Btu/lb) CO_2 and 677 Whr/kg (1,050 Btu/lb) H_2O are the heat generated by the absorption of CO_2 and moisture, respectively.

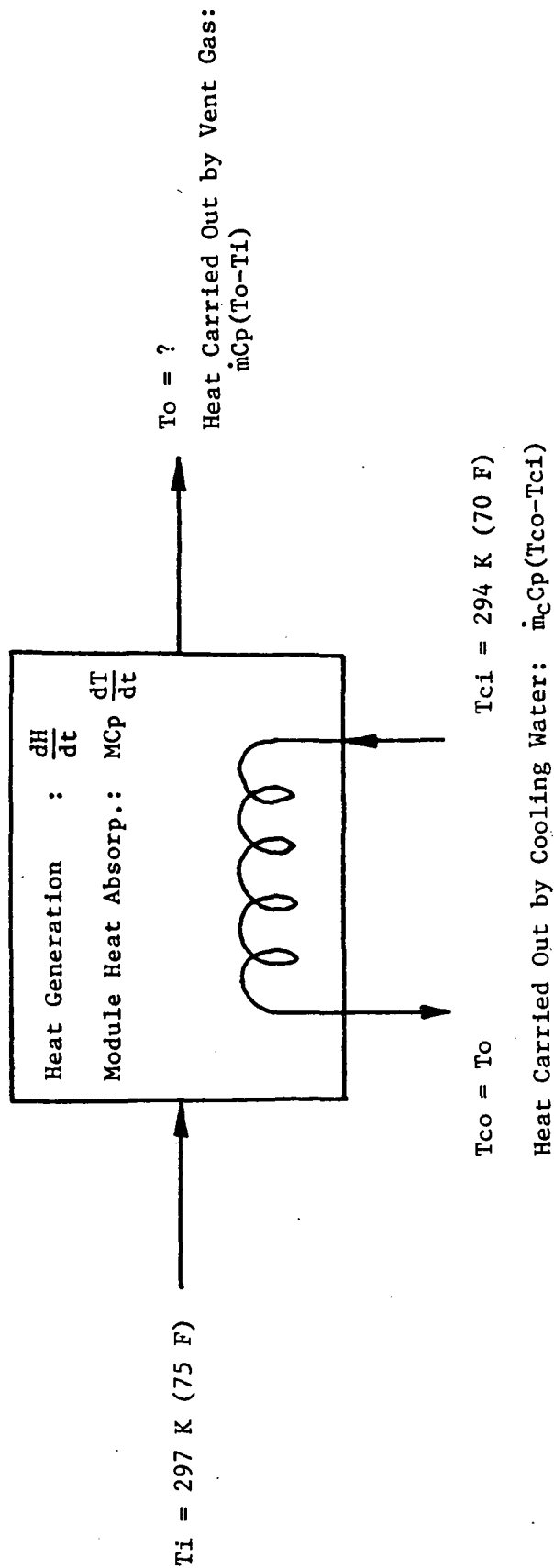


FIGURE 42 ABSORBER MODULE THERMAL BALANCE

Substituting the numerical values of the engineering units to the equation above gives:

$$\begin{aligned} 0.429G &= 24.34 \frac{dT}{dt} + 3.54 (T-75) + 30 (T-61) \\ &= 24.34 \frac{dT}{dt} + 33.54T - 2,095.5 \end{aligned}$$

where:

$$T = T_o$$

Rewriting gives:

$$\frac{dT}{dt} = 86.09 - 1.378 T + 0.01763G$$

Separating the variables and integrating the equation above gives:

$$T = 62.48 + 0.0128G - (0.0128G - 12.52) \text{EXP}(-1.378t)$$

Substitution of the time, t , and the metabolic rate, G , with 0 to 5 hours and 88 to 586 W (300 to 2,000 Btu/hr), respectively, gives the temperature change profile of the absorber module shown in Figure 43. At the metabolic rate of 234 W (800 Btu/hr), the vent gas temperature reaches 296 K (72.7 F) after three hours of EVA. The fact that the vent gas outlet temperature levels off after approximately three hours means the third term of the above equation becomes negligible when t is greater than 3. That is, almost a steady state is reached within three hours of EVA. The cooling water temperature requirements for the steady state vent gas outlet temperatures of 289 to 306 K (60 to 90 F) at various metabolic rates and cooling water flow rates are shown in Table 17. Steady state vent gas outlet temperature as a function of cooling water supply temperature and flow rates at the metabolic rate of 293 W (1,000 Btu/hr) is shown in Figure 44.

Accumulator Design

The conceptual design will utilize an accumulator integrated into the bottom header of the absorber module. This design has advantages over an external accumulator in the following aspects:

1. Reduced plumbing
2. Improved absorbent utilization
3. Improved recharge efficiency
4. Reduced overall envelope volume
5. Reduced weight

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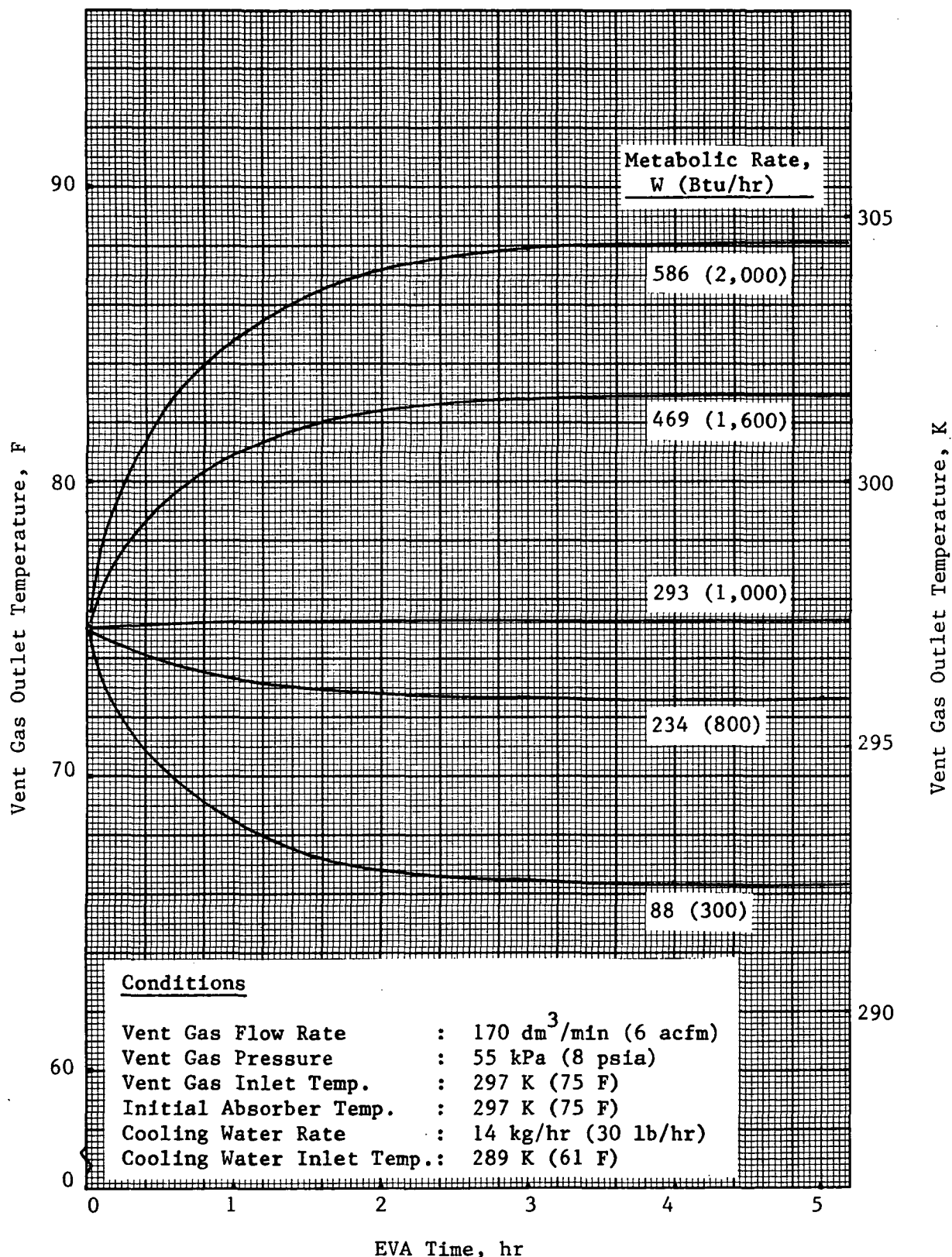


FIGURE 43 VENT GAS OUTLET TEMPERATURE CHANGE WITH EVA TIME

TABLE 17 COOLING WATER TEMPERATURE REQUIREMENTS AT VARIOUS
METABOLIC RATES AND COOLING WATER FLOW RATES

Metabolic Rate, W (Btu/hr)	Cooling Water Rate, kg/hr (lb/hr)	Cooling Water Temperature Requirements, K (F) for Vent Gas Outlet Steady State Temperatures of			
		289 (60)	294 (70)	300 (80)	305 (90)
88 (300)	9.1 (20)	283.7 (50.9)	290.2 (62.6)	296.7 (74.4)	303.3 (86.2)
	13.6 (30)	285.3 (53.9)	291.6 (65.1)	297.8 (76.3)	304.0 (87.5)
	18.1 (40)	286.2 (55.4)	292.2 (66.3)	298.3 (77.2)	304.3 (88.1)
	22.7 (50)	286.7 (56.4)	292.7 (67.1)	298.6 (77.8)	304.6 (88.5)
234 (800)	9.1 (20)	277.7 (40.2)	284.3 (52.0)	290.8 (63.7)	297.3 (75.5)
	13.6 (30)	281.4 (46.8)	287.6 (58.0)	293.8 (69.1)	300.0 (80.3)
	18.1 (40)	283.2 (50.1)	289.3 (61.0)	295.3 (71.9)	301.3 (82.7)
	22.7 (50)	284.3 (52.1)	290.3 (62.8)	296.2 (73.5)	302.2 (84.2)
293 (1,000)	9.1 (20)	275.3 (35.9)	281.8 (47.6)	288.4 (59.4)	295.3 (71.8)
	13.6 (30)	279.8 (43.9)	286.0 (55.1)	292.2 (66.3)	298.5 (77.5)
	18.1 (40)	282.0 (47.9)	288.1 (58.8)	294.1 (69.7)	300.2 (80.6)
	22.7 (50)	283.4 (50.4)	289.3 (61.1)	295.3 (71.8)	301.2 (82.5)
469 (1,600)	9.1 (20)	268.2 (23.0)	274.7 (34.8)	281.3 (46.6)	287.8 (58.3)
	13.6 (30)	275.1 (35.4)	281.2 (46.5)	287.4 (57.7)	293.7 (68.9)
	18.1 (40)	278.4 (41.5)	284.5 (52.4)	290.6 (63.3)	296.6 (74.2)
	22.7 (50)	280.5 (45.2)	286.4 (55.9)	292.4 (66.6)	298.3 (77.3)

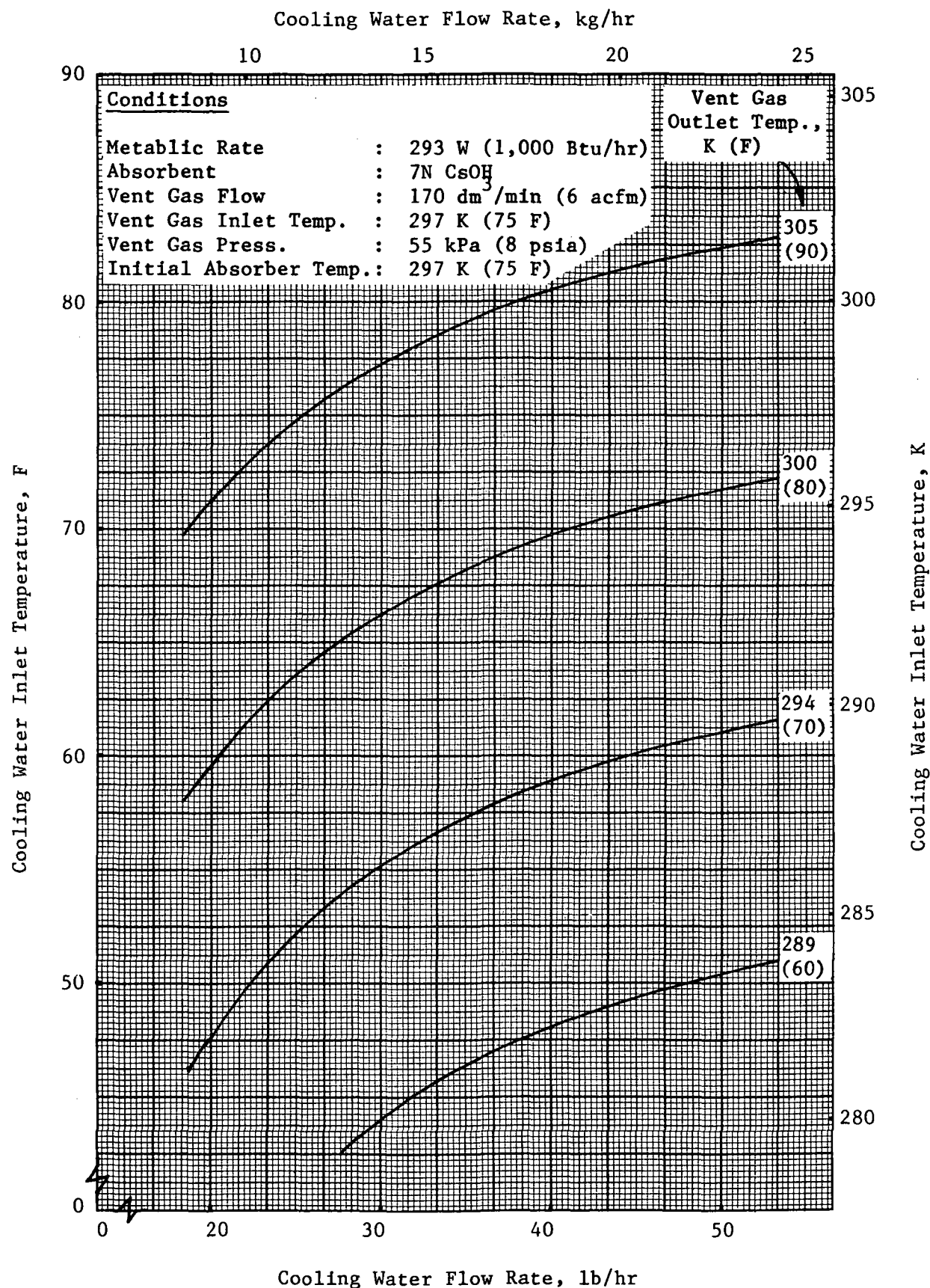


FIGURE 44 VENT GAS OUTLET STEADY STATE TEMPERATURE VERSUS COOLING WATER TEMPERATURE AND FLOW RATE

ERCA PROTOTYPE SUBSYSTEM OPERATION PROCEDURES AND TIMELINE

Prototype Absorber Module Operation Description - Absorption

Figure 45 shows the absorber module in the absorption mode. Table 18 lists the absorber module components. During the EMU checkout, vent gas flow, coolant water flow and absorbent circulation are activated. Four-way absorbent valve, V1, is in the recirculation position. Absorbent from the pump suction side of the top header, TH1, flows to the absorbent circulation pump, PUI. The absorbent then flows via valve V1 through the pump discharge side of the top header where it contacts the cooling heat exchanger, HX1. The absorbent flows through the downstream (with respect to vent gas flow) portion of the absorbent bed, into the bottom header, BH1, and through the upstream portion of the absorbent bed back into the top header. The circulation pump, PUI, speed is monitored by speed sensor S1. Current sensor I1 monitors the pump motor, M1, current.

Vent gas passes through the inlet particulate/trace contaminant filter, GF1. This filter consists of a particulate filter and an activated carbon bed for removal of trace contaminants. The vent gas then enters the absorbent bed, AB1. The absorbent bed is composed of several parallel microporous teflon membranes, arranged in a crossflow configuration with vent gas and liquid absorbent flowing perpendicular to each other in alternate flow compartments. The membranes are hydrophobic, and are thus capable of retaining the liquid absorbent. Gaseous components in the vent gas are able to diffuse through the membrane pores and contact the liquid absorbent. Carbon dioxide can thus be removed from the vent gas by contacting the absorbent solution and reacting with hydroxide ions to form carbonate and then bicarbonate ions. Water vapor is removed from the vent gas due to the difference in water partial pressure of the vent gas and the absorbent. The vent gas, depleted of CO₂ and moisture, passes through a safety membrane which is part of the absorbent bed and located on the downstream side. This membrane is a microporous, hydrophobic membrane which allows vent gas to pass through but retains bulk liquid. Should leakage occur within the absorbent bed, it will be contained by the safety membrane. Any increase in the vent gas pressure drop due to the coverage of the surface of the safety membrane by liquid will be detected by the vent gas differential pressure sensor, P2. A liquid sensor, L1, located between the absorbent bed (downstream of the safety membrane) and the vent gas outlet filter, GF2, will detect possible absorbent leakage from the absorbent bed safety membrane. A secondary hydrophobic membrane is utilized in GF2 to insure that if liquid leakage through the safety membrane is not immediately detected by L1, that it will still be unable to enter the vent gas loop. This low pressure drop membrane provides both particulate removal and liquid retention. Also included in GF2 is a trace contaminant control bed.

The reaction of CO₂ and hydroxide ions and the absorption of water generate heat. This heat must be removed to prevent heating of the vent gas stream and the liquid absorbent. Heat removal is accomplished by cooling the liquid absorbent using the heat exchanger, HX1, in the pump discharge portion of the top header. The cooled absorbent flowing through the downstream portion of the absorbent bed provides cooling of the vent gas prior to its exiting the bed.

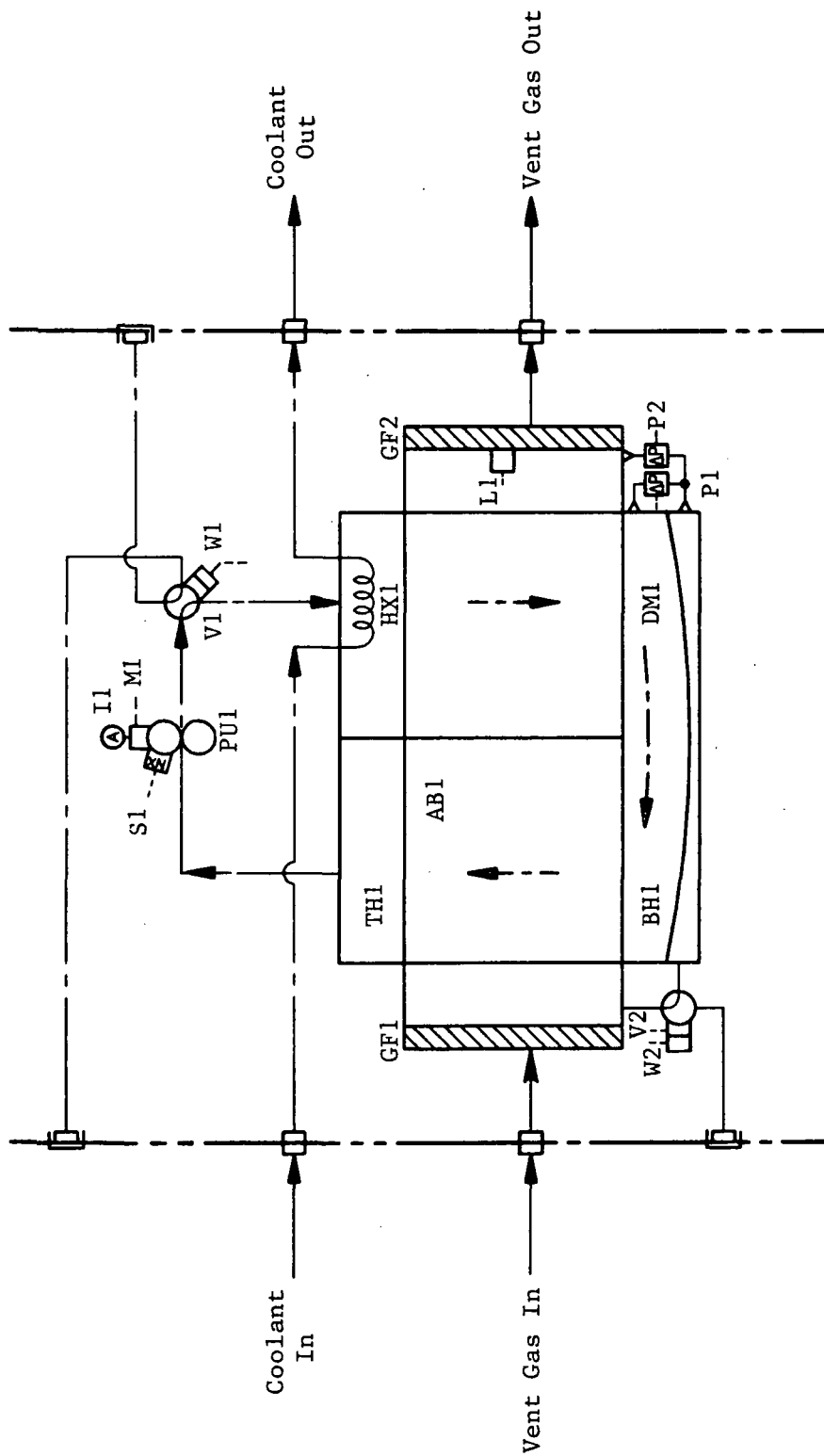


FIGURE 45 ERCA ABSORBER MODULE MECHANICAL SCHEMATIC (ABSORPTION)

TABLE 18 ERCA ABSORBER MODULE COMPONENTS LIST

Component		Function/Description
Name	Part No.	
Absorbent Bed	AB1	Contains absorbent and provides gas-liquid interface area for CO ₂ and water absorption
Top Header	TH1	Contains absorbent and cooling heat exchanger and also provides passage for absorbent circulation
Bottom Header	BH1	Contains absorbent and a diaphragm for absorbent volume change. It also provides passage for absorbent circulation
Circulation Pump	PU1	Circulates absorbent through the absorbent bed and the absorbent headers. Also used in recharge of the module
Motor	M1	Motor for the circulation pump
Four-Way Absorbent Valve	V1	Switches flow from recirculation during absorption to let expanded absorbent flow out and regenerated absorbent flow in during recharge and vice versa
Vent Gas Reference Valve	V2	Provides reference to the gas side of the diaphragm during absorption. Also helps pushing expended absorbent out during recharge by lettering pressurized air in
Diaphragm	DM1	Accommodates the absorbent volume increase/decrease during EVA operation and recharge
Gas Filters	GF1, GF2	Removes particulates and/or trace contaminants from vent gas
Cooling Heat Exchanger	HX1	Cools the absorbent
Current Sensor	I1	Circulation pump current sensor
Speed Sensor	S1	Circulation pump speed sensor
Liquid Sensor	L1	Detects absorbent in the vent gas outlet header
Pressure Sensor	P1	Monitors the differential pressure between the absorbent and the gas sides of the diaphragm
Pressure Sensor	P2	Monitors the differential pressure between the inlet and the outlet vent gas headers
Valve Position Indicator	W1	Indicates valve position of the four-way absorbent valve
Valve Position Indicator	W2	Indicates valve position of the vent gas reference valve

A flexible rubber diaphragm, DMI, is provided in the bottom header to accommodate any liquid absorbent volume expansion which might occur during operation. Absorbent volume expansion is a result of:

- The liquid volume expansion which occurs as hydroxide ions are converted to carbonate/bicarbonate ions by reaction with CO_2 .
- The liquid volume expansion which occurs as moisture is removed from the vent gas and absorbed (condensed) into the absorbent solution.
- Gas dissolved in the liquid absorbent at high pressure which can come out of solution and expand in volume as EMU pressure is reduced. (This can be minimized or eliminated by preconditioning the absorbent under vacuum.) If these gas bubbles form near the membrane, they will pass through it into the vent gas loop, not causing a problem. The circulation of absorbent will help bubbles come in contact with membranes. The bubbles formed in the places where they cannot contact and pass through the membranes, will temporarily produce an expansion in the liquid compartment volume until they are moved to the membrane surfaces by the circulating absorbent.

By accommodating the liquid volume expansion, the diaphragm eliminates any unnecessary stress on the membranes. Should the diaphragm become fully extended, further liquid volume increases result in stretching of the membranes. The resistance of the membranes to stretching creates a pressure build-up within the liquid compartments, such that a differential pressure is observed between the liquid and vent gas. This increased differential pressure is detected by a differential pressure sensor P1.

The available diaphragm displacement volume is based on the CO_2 and moisture absorption anticipated for the five-hour EVA and the expected dissolved gas evolution during depressurization. This initial volume is obtained by extending the diaphragm toward the liquid compartment using a low pressure air source to the gas side of the diaphragm during absorbent charging (see Figure 46). When charging is complete, the low pressure air is discontinued and the gas side of the diaphragm is referenced to the vent gas by way of the three-way solenoid valve, V2. This establishes the same differential pressure reference for the liquid and gas sides of the diaphragm and the liquid and gas sides of the membranes. Because of the low resistance of the diaphragm to changes in differential pressure, compared to the membrane (which is well supported by spacer screens), it responds quickly to eliminate differential pressure by accommodating volume. Thus, the membranes are not exposed to any significant differential pressure.

The vent gas differential pressure across the absorbent bed is monitored by differential pressure sensor, P2. The vent gas inlet reference to P2 is by way of valve V2 and the gas side of the bottom header.

Prototype Absorber Module Operation Description - Recharge

Figure 46 shows the absorber module in its recharge mode. During the Servicing/Recharge portion of the EVA's operational duty cycle, the expended

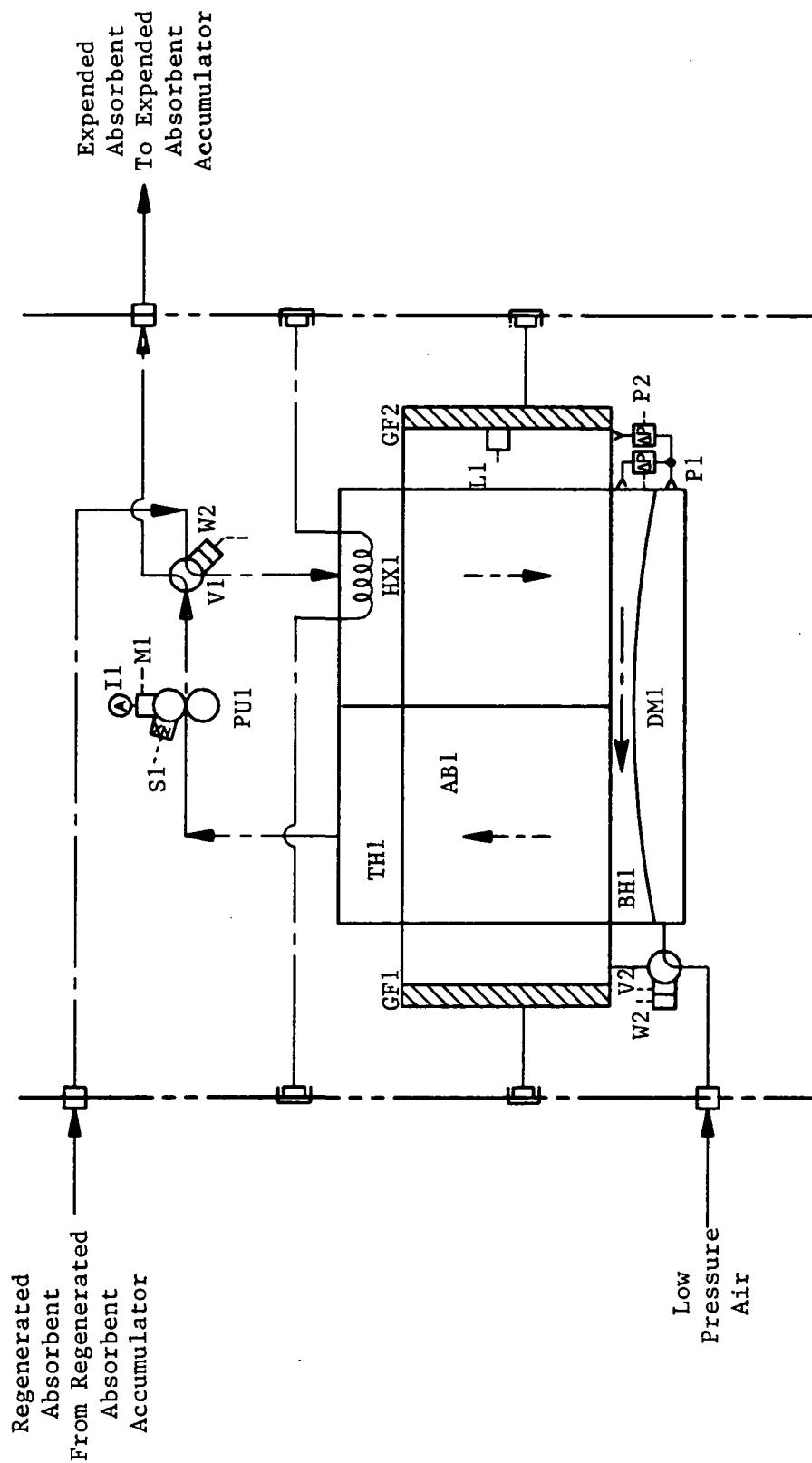


FIGURE 46 ERCA ABSORBER MODULE MECHANICAL SCHEMATIC (RECHARGE)

absorbent in the Absorber Module is replaced with regenerated absorbent. The quick disconnects on the inlet and outlet hoses of the regenerator module are attached to the quick disconnects of the absorber module absorbent outlet and inlet, respectively. Four-way absorbent valve, V1, is switched to the recharge position. The regenerated absorbent storage tank, TK2, and expended absorbent storage tank, TK1, are prepared for absorbent recharge by opening the associated shutoff valves (refer to the Electrochemical Regenerator Subsystem Operation Description).

A low pressure air hose is attached to the quick disconnect on the absorber module by valve V2. The diaphragm, DM1, is returned to the initial position by pressurizing the gas side with low pressure air by way of the vent gas reference valve, V2. The expended absorbent on the liquid side of the diaphragm in the bottom header is pushed through the upstream side of the absorbent bed into the top header and out via PUL to the expended absorbent storage tank. The low pressure air to the diaphragm remains on until the recharge is complete, at which time the valve V2 is switched back to the vent gas reference. The absorbent circulation pump, PUL, is turned on to begin circulation of regenerated absorbent through the absorber module. Regenerated absorbent from the regenerated absorbent storage tank passes through the valve V1 and flows into the top header, TH1, displacing expended absorbent. The flow continues through the downstream portion (with respect to vent gas flow) of the absorbent bed, AB1, through the bottom header, BH1 and through the upstream portion of the absorbent bed back into the top header. Displaced expended absorbent flows from the top header and through the circulation pump, PUL, and is collected in the expended absorbent storage tank. The absorbent flow path within the top and bottom headers and within the absorbent bed is arranged to optimize the displacement of the expended absorbent. This is accomplished by providing narrow flow passages which minimize the mixing at the regenerated absorbent/expended absorbent interface.

All fault detection monitors are operating during the absorber module recharge, including the speed sensor, S1, the current sensor, I1, the liquid sensor, L1, the diaphragm differential pressure sensor, P1 and the vent gas differential pressure sensor, P2.

Prototype Electrochemical Regenerator Subsystem Operation Description

Figure 47 shows the Electrochemical Regenerator Subsystem Mechanical Schematic. Table 19 lists the components. Expended absorbent from the Absorber Module is collected in the expended absorbent storage tank, TK1, by opening shutoff valve V1. The expended absorbent is supplied at sufficient pressure to overcome the gas reference pressure, allowing movement of the bellows. Filling of TK1 can be performed with the electrochemical regenerator operating (shutoff valve V2 open). TK1 is equipped with quantity sensor Q1, which provides an indication of the amount of expended absorbent within the tank. Expended absorbent from TK1 is supplied to the Electrochemical Regenerator, ER1, via shutoff valve V2. The expended absorbent combines with the absorbent circulation stream and enters the circulation pump, PUL. The circulation pump speed is monitored by the pump speed sensor, S1. The pump motor, M1, current is monitored by the pump current sensor, I2. An electric absorbent heater,

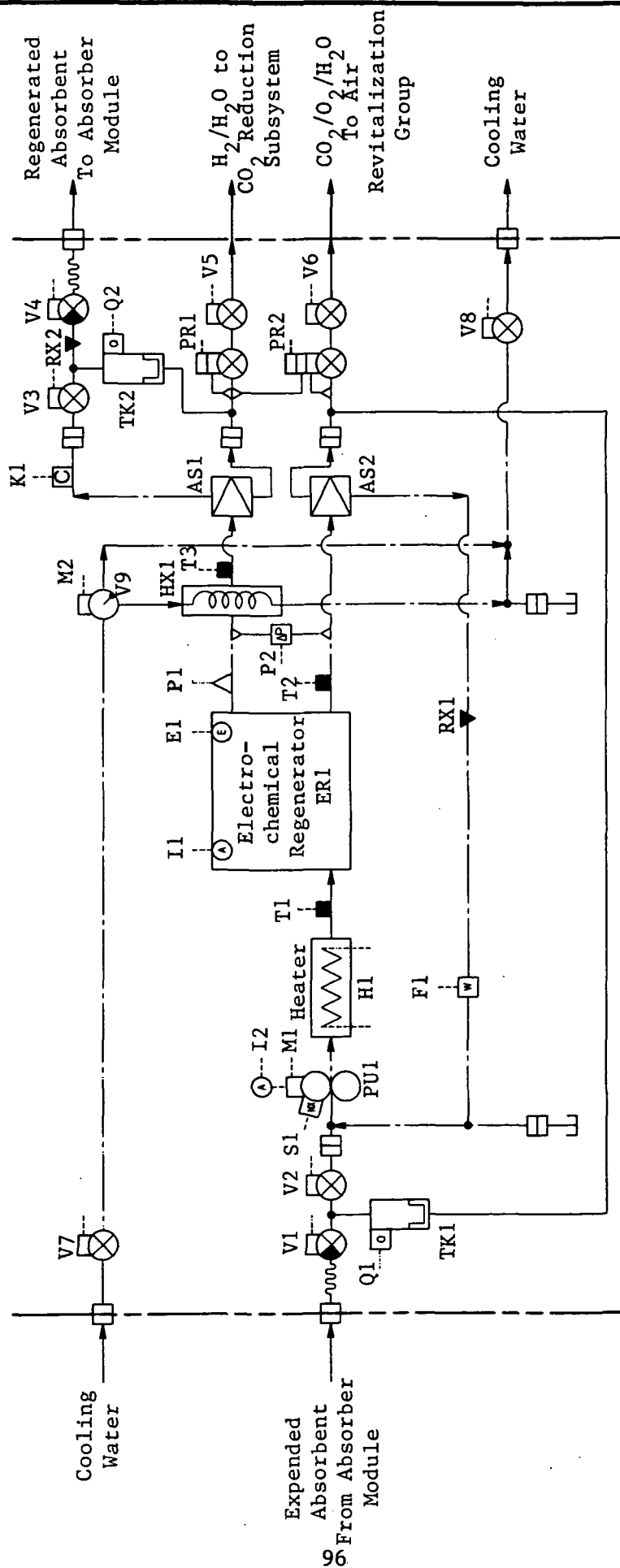


FIGURE 47 ERCA ELECTROCHEMICAL REGENERATOR SUBSYSTEM MECHANICAL SCHEMATIC

TABLE 19 ERCA ELECTROCHEMICAL REGENERATOR SUBSYSTEM COMPONENTS LIST

Component		Part No.	Function/Description
Name			
Electrochemical Regenerator	ER1		Electrochemically regenerates expended absorbent
Circulation Pump	PU1		Circulates expended absorbent through the regenerator
Absorbent Heater	H1		Adds heat to circulating expended absorbent
Regenerated Absorbent Separator	AS1		Separates regenerated absorbent from H ₂ and water vapor
Expended Absorbent Separator	AS2		Separates expended absorbent from CO ₂ , O ₂ and water vapor
Cathode Pressure Regulator	PR1		Regulates the pressure of the cathode compartment
Electrodes Differential Pressure Regulator	PR2		Regulates the differential pressure between the anode and the cathode compartments
Circulation Flow Restrictor	RX1		Restricts expended absorbent circulation
Regenerated Absorbent Flow Restrictor	RX2		Restricts the flow of the regenerated absorbent to the absorber module
Expended Absorbent Storage Tank	TK1		Stores expended absorbent
Regenerated Absorbent Storage Tank	TK2		Stores regenerated absorbent
Cooling Heat Exchanger	HX1		Cools regenerated absorbent
Shutoff Valve	V1		Expended absorbent shutoff
Shutoff Valve	V2		Shutoff between the expended absorbent storage tank and the expended absorbent circulation loop
Shutoff Valve	V3		Shutoff between the regeneration stream and the regenerated absorbent storage tank
Shutoff Valve	V4		Shutoff between the regenerated absorbent tank and the absorber module
Shutoff Valve	V5		Isolates H ₂ /water vapor stream from downstream
Shutoff Valve	V6		Isolates CO ₂ /O ₂ /water vapor stream from downstream
Shutoff Valve	V7		Shuts off the flow of cooling water
Shutoff Valve	V8		Isolates cooling water stream from downstream
Diverter Valve	V9		Diverts the flow of cooling water through the cooling heat exchanger
Circulation Pump Motor	M1		Motor for the expended absorbent circulation pump
Diverter Valve Motor	M2		Motor for the cooling water diverter valve
Regenerator Current Sensor	I1		Monitor the current to the electrochemical regenerator module
Pump Current Sensor	I2		Monitors the current to the expended absorbent circulation pump

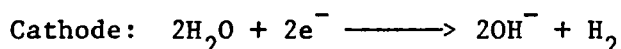
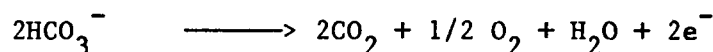
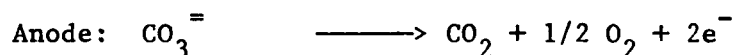
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Table 19 - continued

Component		Part No.	Function/Description
Name			
Regenerator Voltage Sensor	E1		Monitors the voltage of the electrochemical regenerator module
Expended Absorbent Circulation Flow Sensor	F1		Monitors the circulation of expended absorbent
Pressure Sensor	P1		Monitors the pressure of the cathode compartment
Diff. Pressure Sensor	P2		Monitors the differential pressure between the anode and the cathode compartments
Inlet Temperature Sensor	T1		Monitors the regenerator inlet temperature of the expended absorbent
Outlet Temperature Sensor	T2		Monitors the regenerator outlet temperature of the expended absorbent
Regenerated Absorbent Temperature Sensor	T3		Monitors the temperature of the regenerated absorbent downstream of the cooling heat exchanger
Pump Speed Sensor	S1		Monitors the speed of the expended absorbent circulation pump
Expended Absorbent Quantity Sensor	Q1		Monitors the amount of expended absorbent in TK1
Regenerated Absorbent Quantity Sensor	Q2		Monitors the amount of regenerated absorbent in TK2
Regenerated Absorbent Conductivity Sensor	K1		Monitors the conductivity of regenerated absorbent

H1, provides the desired absorbent circulation temperature at the outlet of ER1, as indicated by the thermocouple T2. This heater is generally required only during startup since the regeneration process generates heat. The expended absorbent temperature at the inlet of ER1 is monitored by thermocouple T1.

The expended absorbent enters the electrochemical regenerator and flows through the anode compartment. The current and the voltage of the regenerator are monitored by I1 and E1. A portion of the expended absorbent passes through the electrode core where the carbonate and bicarbonate ions are converted to hydroxide ion by the following reactions:



In addition to the conversion of $\text{CO}_3^{=}$ and HCO_3^- to OH^- , the regeneration process consumes water. This is the water which had been removed from the vent gas by the absorbent during absorber module operation.

Gaseous CO_2 and oxygen (O_2) are evolved at the anode and leave the electrochemical regenerator with the expended absorbent circulation. The two-phase stream flows to the expended absorbent separator, AS2, where the absorbent is separated from the gas. The expended absorbent circulation returns to the circulation pump via a restricting orifice, RX1, which provides backpressuring of AS2, and the expended absorbent circulation flow sensor, F1, which monitors the expended absorbent circulation rate.

The gas stream from AS2, consisting of the O_2 , CO_2 and water vapor, flows through the electrode differential pressure regulator, PR2. This regulator maintains a desired differential pressure between the anode and cathode compartments. This differential pressure provides the driving force that allows a portion of the expended absorbent to flow across the electrode core and become regenerated. PR2 is referenced to the cathode gas outlet pressure and maintains the desired differential pressure regardless of the absolute cathode pressure. The anode-to-cathode differential pressure is monitored by the differential pressure sensor, P2. The anode gas provides the pressure reference to the expended absorbent storage tank, TK1, thus maintaining the tank and expended absorbent circulation at the anode compartment pressure. The anode gas stream passes through shutoff valve V6 and is transferred to the Air Revitalization Group.

The expended absorbent which passes through the electrode core passes through the anode, matrix and cathode, being converted from a carbonate/bicarbonate solution to a concentrated hydroxide solution and being depleted of excess water. Gaseous H_2 is also generated at the cathode. Thus, a mixture of regenerated absorbent and H_2 leaves ER1 from the cathode compartment. The pressure of the cathode outlet stream is monitored by pressure sensor P1. The

cathode outlet is then cooled in the cooling heat exchanger, HX1. HX1 serves to cool the cathode outlet stream, thus reducing the water vapor content of the H_2 . This cooling provides some control over the amount of water which is carried out with the H_2 , and thus controls the total solute concentration of the regenerated absorbent. The temperature of the cathode outlet stream is monitored downstream of HX1 by thermocouple T3. The stream then enters the regenerated absorbent separator, AS1, which is similar to AS2. The H_2 (and water vapor) stream from AS1 flows through the cathode pressure regulator, PR1. This regulator maintains the cathode at the desired absolute pressure. The cathode gas stream passes through shutoff valve V5 and is transferred to the CO_2 Reduction Subsystem. The regenerated absorbent from AS1 passes through the regenerated absorbent conductivity sensor, K1. This sensor allows determination of the regenerated absorbent quality. The regenerated absorbent then flows through shutoff valve V3 and into the regenerated absorbent storage tank, TK2. The amount of regenerated absorbent in TK2 is monitored by the regenerated absorbent quantity sensor Q2. The cathode gas (upstream of PR1) provides the pressure reference to TK2, thus maintaining the tank at the cathode compartment pressure. Shutoff valve V4 is opened when regenerated absorbent is required for absorber module recharge. Restriction orifice, RX2, limits the rate at which regenerated absorbent is supplied to the absorber module. Absorber module recharge can be performed with ER1 operating.

Cooling water flow to HX1 passes through shutoff valve V7 and is diverted to either HX1 or to bypass using diverter valve V9. The diverter valve position is controlled to maintain the desired cathode outlet stream temperature at T3. Cooler T3 temperature is provided by diverting cooling water flow to the heat exchanger, with warmer temperatures provided by diverting flow to bypass. The cooling water outlet flow passes through shutoff valve V8. Ports are provided for draining the cooling water and absorbent circulation loops, if servicing of the subsystem is required.

Operating Mode Definitions and Mode Transition Sequences

The operating modes and mode transition sequences of the absorber module and the electrochemical regenerator subsystem have been defined and are listed in Figure 48 and Tables 20 and 21 for the absorber module and in Figure 49 and Tables 22 and 23 for the electrochemical regenerator subsystem.

Time-Lining of ERCA System Operations

For the time-lining study of the ERCA system operation and service, the following 12 stages have been used.

1. EVA Preparation
2. Don EMU
3. Checkout EMU
4. Egress Airlock (into Crewlock)
5. Egress Crewlock (into Space)
6. Conduct EVA
7. Ingress Crewlock
8. Ingress Airlock

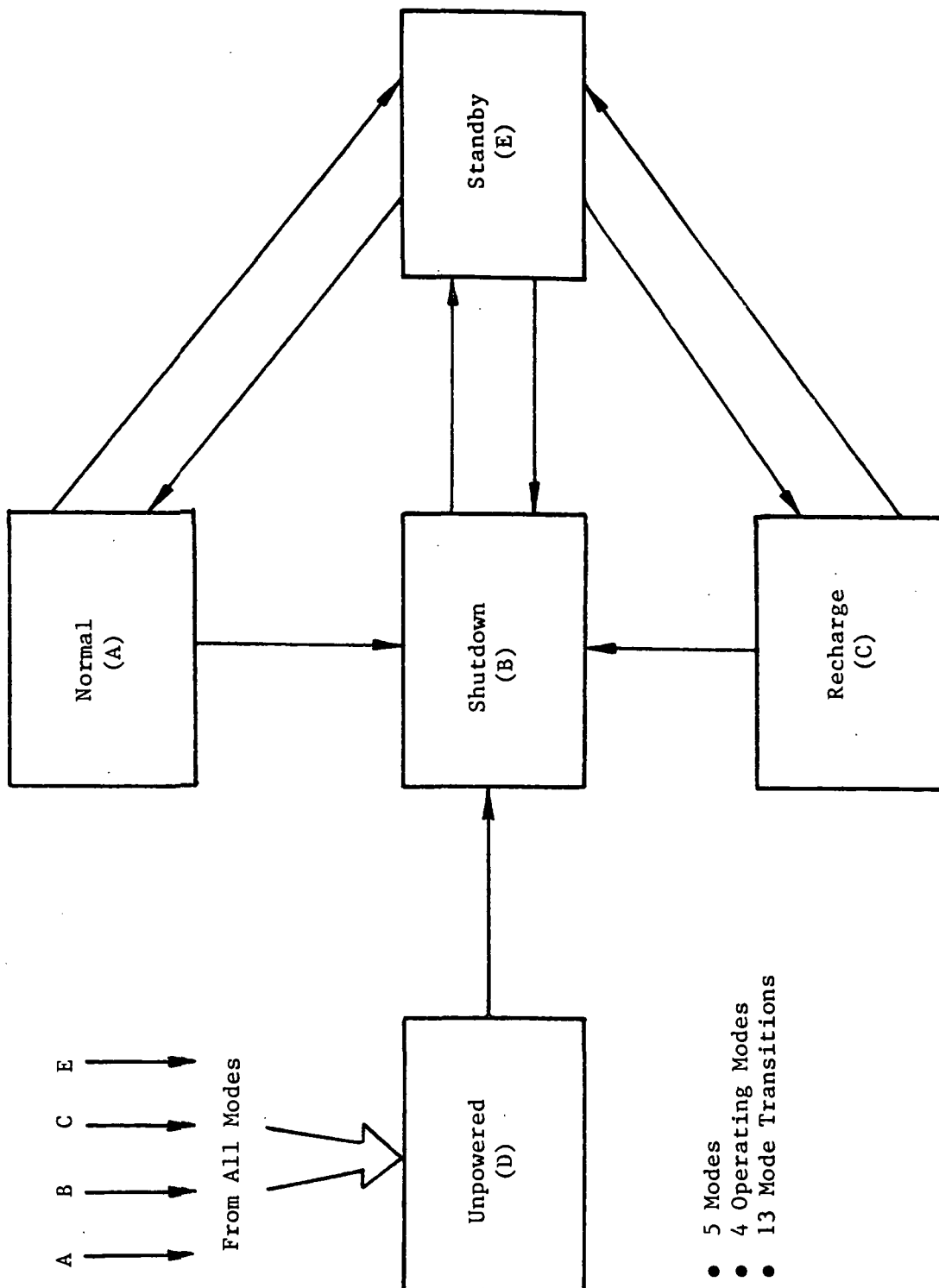


FIGURE 48 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS FOR ABSORBER MODULE

TABLE 20 ABSORBER MODULE OPERATING MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	<p>No fluid flows through the subsystem. The absorbent pump, PU1, is off. The 4-way absorbent valve, V1, is in the absorbent circulation position. The vent gas reference valve, V2, is open to the vent gas header. The subsystem is powered and all sensors and readouts are working. This mode is called for by:</p> <ul style="list-style-type: none">● Manual actuation
Normal (A)	<p>The Absorber Module is absorbing CO₂ and H₂O from the vent gas stream. The absorbent pump, PU1, is on. The 4-way valve, V1, is open for circulating absorbent in the module. The vent gas reference valve, V2, is open to the vent gas header. Coolant is flowing through HX1. All sensors and actuators are working. This mode is called for by:</p> <ul style="list-style-type: none">● Manual actuation
Standby (E)	<p>The vent gas is bypassing the Absorber Module. Coolant flow to HX1 is off. All sensors and actuators are working and the module is at normal operating conditions. This mode is called for by:</p> <ul style="list-style-type: none">● Manual actuation● Low or high differential pressure (P1)● Low or high differential pressure (P2)● Liquid detection (L1)● Low pump speed (S1)● Low or high motor current (I1)
Unpowered (D)	<p>No power is applied to the module. This mode is called for by:</p> <ul style="list-style-type: none">● Manual actuation● Power failure
Recharge (C)	<p>The Absorber Module is being recharged with regenerated absorbent (EMU in post-EVA service, recharge). The absorbent pump, PU1, is on. The 4-way absorbent valve, V2, is open for exchanging the spent absorbent in the module with regenerated absorbent. The vent gas reference valve, V2, is open to a low pressure air source. The subsystem is powered and all sensors and actuators are working. This mode is called for by:</p> <ul style="list-style-type: none">● Manual actuation

TABLE 21 ABSORBER MODULE MODE TRANSITION SEQUENCES

Shutdown to Standby (B to E)

- Turn on the absorbent circulation pump, PU1

Standby to Normal (E to A)

- Start cooling water flow through HX1
- Start vent gas flow through the absorbent bed

Normal to Standby (A to E)

- Stop vent gas flow
- Stop cooling water flow through HX1

Standby to Shutdown (E to B)

- Turn off the absorbent circulation pump, PU1

Normal to Shutdown (A to B)

- Stop vent gas flow
- Turn off the absorbent circulation pump, PU1
- Stop cooling water flow through HX1

Standby to Recharge (E to C)

- Switch 4-way absorbent valve, V1, to the absorbent recharge position
- Switch vent gas reference valve, V2, to the low pressure air source

Recharge to Standby (C to E)

- Switch 4-way absorbent valve, V1, to the absorbent circulation position
- Switch vent gas reference valve, V2, to the vent gas header

Recharge to Shutdown (C to B)

- Switch 4-way absorbent valve, V1, to the circulation position
- Switch vent gas reference valve, V2, to the vent gas header

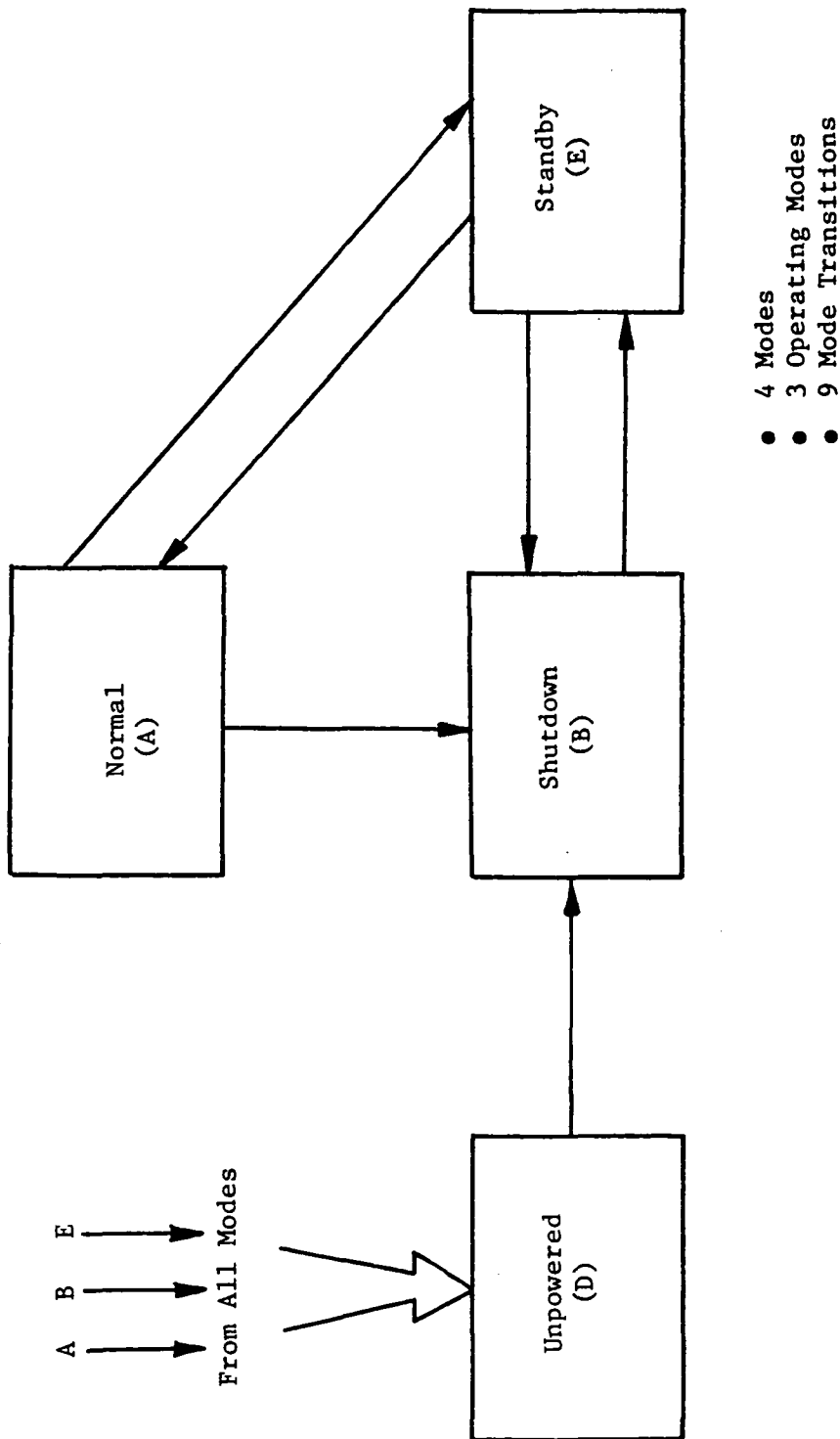


FIGURE 49 OPERATING MODES AND ALLOWABLE MODE TRANSITIONS FOR
ELECTROCHEMICAL REGENERATOR SUBSYSTEM

TABLE 22 ELECTROCHEMICAL REGENERATOR SUBSYSTEM OPERATING MODE DEFINITIONS

Mode (Code)	Definition
Shutdown (B)	<p>No flow of absorbent, coolant or gas through the Electrochemical Regenerator, ER1. The power supply is off. The circulation pump, PU1, and absorbent heater, H1, are off. All shutoff valves, V1 through V8, are closed. The regenerator is depressurized and anode-to-cathode differential pressure is zero. The subsystem is powered and all sensors and readouts are working. This mode is called for by:</p> <ul style="list-style-type: none"> • Manual actuation • Low absorbent flow (F1) • High or low differential pressure (P2) • High or low pressure (P1) • High or low temperature (T2) • Low pump speed (S1) • Low or high motor current (I2) • High or low voltage (E1) • High or low current (I1) • Improper regenerated absorbent quality (K1) • High or low expended absorbent level (Q1) • High or low regenerated absorbent level (Q2)
Normal (A)	<p>The Electrochemical Regenerator is regenerating expended absorbent. Shutoff valves, V2, V3, V5 through V8 are open. Circulation pump, PU1, is on. Absorbent heater, H1, is maintaining the desired regenerator temperature (T2). Pressure regulators, PR1 and PR2, are maintaining desired regenerator pressure (P1) and differential pressure (P2). Diverter valve, V9, is controlling coolant flow to HX1 to maintain desired anode outlet temperature (T3). All sensors and actuators are working and all fault detection is on. This mode is called for by:</p> <ul style="list-style-type: none"> • Manual actuation
Standby (E)	<p>The power supply to the Electrochemical Regenerator is off. Absorbent is circulating through the regenerator at operating temperature. The regenerator is depressurized and the anode-to-cathode differential pressure is zero. All sensors and actuators are working and all fault detection is on. This mode is called for by:</p> <ul style="list-style-type: none"> • Manual actuation
Unpowered (D)	<p>No power is applied to the subsystem. This mode is called for by:</p> <ul style="list-style-type: none"> • Manual actuation • Power failure

TABLE 23 ELECTROCHEMICAL REGENERATOR SUBSYSTEM MODE TRANSITION SEQUENCES

Shutdown to Standby (B to E)

- Open the pressure regulators, PR1 and PR2
- Open shutoff valves, V2, V3, V5, V6, V7 and V8
- Turn on the circulation pump, PU1
- Turn on the absorbent heater, H1, to maintain desired temperature at T2.

Standby to Normal (E to A)

- Turn on the regenerator power supply
- Adjust PR1 at TBD psig at P1
- Adjust PR2 at TBD psid at P2
- Adjust diverter valve, V9, to maintain desired temperature at T3.

Normal to Standby (A to E)

- Open PR1 and PR2
- Turn off the module power supply

Standby to Shutdown (E to B)

- Turn off the absorbent heater, H1
- Turn off the circulation pump, PU1
- Close shutoff valves, V2, V3, V5, V6, V7 and V8.

Normal to Shutdown (A to B)

- Turn off the regenerator power supply
- Turn off the absorbent heater, H1
- Turn off the absorbent circulation pump, PU1
- Open PR1 and PR2 (to depressurize)
- Close shutoff valves, V2, V3, V5, V6 V7 and V8
- Close PR1 and PR2

9. Doff EMU
10. Post EVA Checkout
11. Service and Maintenance
12. Egress Airlock (into Space Station)

Figure 50 shows where these activities occur.

The activities required for the ERCA System at various stages are described below.

EVA Preparation

During the EVA preparation stage a crewman gets the airlock ready to enter, enters the airlock and prepares for an EVA. The connections of the Absorber Module to the Electrochemical Regenerator subsystem and to the low pressure air should be disconnected. This will take less than one minute.

Don EMU

The last activity in the stage, when activities such as checking and verification of various EMU components statuses, donning the space suit and connecting of the liquid cooled garment (LCG) are performed, should be the initiation of absorbent circulation of the Absorber Module after closing the rear entry of the space suit. This will take less than 0.2 minutes.

EMU Checkout

The confirmation of the absorbent circulation pump operation should be included as a part of the EMU checkout, which includes activities such as EMU pressure/leak check, checkout of O_2 and cooling water flow, and checkout of CO_2 level.

Doff EMU

After the airlock pressure is equalized to the cabin pressure and the EMU is attached to a donning station, absorbent circulation in the Absorber Module is deactivated before opening the rear entry.

Service, Recharge and Maintenance

The automatic service, recharge and maintenance of the absorber module after an EVA will consist of the following steps to be completed in the times as indicated (refer to Figures 45, 46 and 47 and Tables 18 and 19 for the identification of functions of the components). The "a" and "r" in the parentheses denote the Absorber Module and the Electrochemical Regenerator subsystem, respectively.

- | | |
|--|-----|
| 1. Attach absorbent and air hoses to EMU | 0.2 |
| 2. Switch V1 (a) to recharge position | 0.2 |
| 3. Open V1 and V4 (r) | 0.2 |
| 4. Switch V2 (a) | 0.2 |

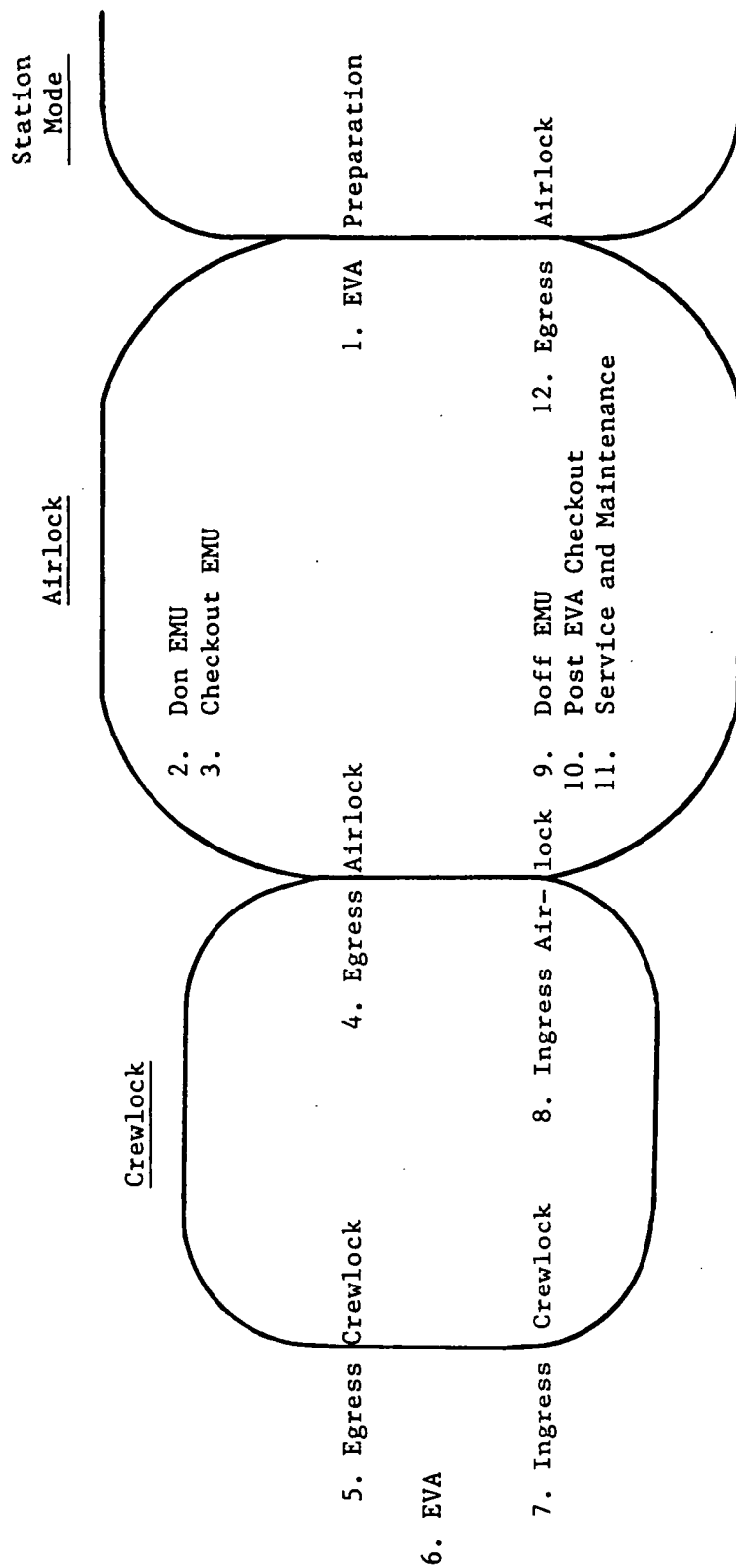


FIGURE 50 LOCATION OF TWELVE STAGES OF EVA

5.	Start PU1 (a)	0.2
6.	Perform recharge of the absorber module	30.0
7.	Stop PU1 (a)	0.2
8.	Close V1 and V4 (r)	0.2
9.	Switch V1 (a)	0.2
10.	Switch V2 (a)	0.2
11.	Disconnect absorbent and air hoses	0.2
12.	Open V2 and V3 (r)	0.2
13.	Open V5 and V6	0.2
14.	Start PU1 (r)	0.2
15.	Start H1 and warm up the system	10.0
16.	Open V7 and V8	0.2
17.	Start current and adjust pressure	5.0
18.	Regeneration	600.0
19.	Stop current and reduce pressure	3.0
20.	Stop H1 and cool	10.0
21.	Close V7 and V8	0.2
22.	Stop PU1 (r)	0.2
23.	Close V2 and V3 (r)	0.2
24.	Close V5 and V6 (r)	0.2

As can be seen in the scenario above, the first eleven steps are for the recharge of the absorber module. The total time required for the recharge is 32.0 minutes. The absorber module recharge time can be shorter by using higher recharge flow rate if needed.

The steps 12 through 24 are for the regeneration of the expended absorbent and its related preparation activities, for which 629.6 minutes (= 10.5 hours) are allocated to complete the entire service of the system within 12 hours. The regeneration time can also be reduced by using an electrochemical regenerator module of larger capacity or by performing the regeneration concurrently with the recharge.

Based on the time requirements for the recharge/extraction of the Absorber Module and the regeneration of expended absorbent, EVA operation - Absorber Module recharge - Regeneration of expended absorbent time lines have been prepared and shown in Figure 51 for three different cases; i.e., no spare absorbent, one absorber volume spare absorbent and two absorber volume spare absorbent cases. For each case, maximum possible annual EVA hours have been estimated. As can be seen in Figure 51, without any spare absorbent, one person EVA of up to 2,615 hours per year can be performed; whereas with two absorber volume spare absorbent, up to 5,006 hours of EVA can be performed when two persons perform EVA at the same time.

CONCLUSIONS

The following conclusions were reached as a result of the program activities:

1. The Absorber Module meets or exceeds the CO₂ removal requirements specified for the design. It can also meet the moisture removal requirement when proper cooling is provided.

No. of Spare Absorbent	EVA/Recharge/Regeneration Time-Lines	Max. EVA hr/yr
0	<p>a. One Person</p> <p>b. Two Persons - Simultaneous EVA</p>	<p>2,615</p> <p>3,893</p>
1	<p>a. One Person</p>	3,728
2	<p>a. Two Persons - Simultaneous EVA</p>	5,006

(a) a. can be achieved by increasing regeneration rate by 50%.

FIGURE 51 EVA/RECHARGE/REGENERATION TIME-LINES

2. The absorbent bed using microporous hydrophobic membrane sheets with circulating absorbent is the best approach to the design of an Absorber Module based on sizing and performance.
3. Regeneration of expended absorbent can be achieved by an electrochemical method using the electrochemical cells employed in the testing.
4. The breadboard and projected flight hardware weight, power and volume information is provided in Table 24.
5. Absorption of metabolic CO₂ and moisture for PLSS by using liquid absorbent has many advantages over solid absorbent, which include:
 - Minimum volume and weight
 - Efficient moisture removal
 - Flexible design and operation
 - Simple recharge process
 - Absorbent state determinable
6. The state of absorbent can be determined by measuring conductivity or pH of the absorbent.
7. The best absorbent for ERCA is cesium absorbent. Its bicarbonate salt has high solubility, it has lower heat of reaction and lower water vapor pressure (than other absorbents).

RECOMMENDATIONS

The following recommendations are direct results of the work completed:

1. Design optimization tests using subscale absorbent beds should be initiated for further reduction of the absorber module volume and weight.
2. Demonstration tests for the safety design should be initiated for the verification of their performance.
3. Further parametric testing of the electrochemical regeneration should be performed to identify optimum electrochemical cell configuration and operating conditions.
4. A development program should be initiated for the life testing of the Absorber Module and the Electrochemical Regenerator to identify the kinetic limits of the system and proper operation ranges.
5. Development of zero-G-compatible gas-liquid separation devices for the separation of regenerated absorbent from gases or water vapors should be initiated.

TABLE 24 ERCA SYSTEM PHYSICAL CHARACTERISTICS

<u>Breadboard</u>	<u>CO₂/H₂O Absorber Module</u>	<u>Electrochemical Regenerator Module</u>	<u>Electrochemical Regenerator Subsystem</u>
Dimension, cm (in) W x H x L	28.0 x 35.3 x 17.8 (11.0 x 13.9 x 7.0)	25.4 x 33.5 x 24.1 (10.0 x 13.2 x 9.5)	-
Volume, dm ³ (ft ³)	17.6 (0.62)	20.7 (0.73)	
Weight, kg (lb)	24.4 (54)	26.4 (58)	-
Power, W	1.5	450	-
<u>Flight</u>			
Volume, dm ³ (ft ³)	14.7 (0.52)	18.7 (0.66)	69 (2.4)
Weight, kg (lb)	20.4 (45)	23.6 (52)	42 (93)
Power, W	1.0	400	450

REFERENCES

1. Colombo, G. V., "Study of CO₂ Sorbents for Extravehicular Activity," Final Report, Contract NAS2-6959, NASA CR-114632; McDonnell Douglas Astronautics Company, Huntington Beach, CA; July, 1973.
2. Berzins, V. and Ross, L. W., "Carbon Dioxide Absorption in Packed Beds of Alkaline Carbonate Materials," Paper No. 77-ENAS-17, presented by the American Society of Mechanical Engineers at the Intersociety Conference on Environmental Systems, San Francisco, CA; July, 1977.
3. Onischak, M., "Development of a Prototype Regenerable Carbon Dioxide Absorber," Final Report, Contract NAS2-8644, NASA CR-137919; Energy Research Corp., Danbury, CT; September, 1976.
4. Onischak, M. and Baker, B., "Carbon Dioxide Absorbent Study," Final Report, Contract NAS2-7023, NASA CR-114661; Energy Research Corp., Bethel, CT; September, 1973.
5. Patel, P. S. and Baker, B. S., "Development of a Prototype Regeneration Carbon Dioxide Absorber," Final Report, Contract NAS2-9265, NASA CR-152063; Energy Research Corp., Danbury, CT; October, 1977.
6. "Extravehicular Crewman Work System (ECWS) Study Program," Contract NAS9-15290, Study No. 6, Regenerable CO₂ Removal; Hamilton Standard Windsor Locks, CT; March, 1978.
7. Woods, R. R. and Marshall, R. D., "Electrochemical Regenerable Carbon Dioxide Absorber," Annual Report, Contract NAS2-8666, NASA CR-151957, ER-290-5; Life Systems, Inc., Cleveland, OH; January, 1977.
8. Woods, R. R., Marshall, R. D., Schubert, F. H. and Heppner, D. B., "Electrochemically Regenerable Carbon Dioxide Absorber," Final Report, Contract NAS2-8666, NASA CR-152099, ER-290-3; Life Systems, Inc., Cleveland, OH; August, 1979.
9. Heppner, D. B., Woods, R. R. and Schubert, F. H., "Regenerative CO₂ Removal for PLSS Application," Final Report, Contract NAS9-15218, TR-319-31-6; Life Systems, Inc., Cleveland, OH; October, 1979.
10. Tosh, J. S., Field, J. H., Benson, H. E. and Haynes, W. P., "Equilibrium Study of the System Potassium Carbonate, Potassium Bicarbonate, Carbon Dioxide and Water," The Bureau of Mines Report of Investigations 5484, 1959.